Technical Memo

ANL/EES-TM-229

COSTS AND AIR QUALITY IMPACTS OF ALTERNATIVE NATIONAL AMBIENT AIR QUALITY STANDARDS FOR PARTICULATE MATTER

Technical Support Document

ARGONNE NATIONAL LABORATORY
Energy and Environmental Systems Division

operated for
U. S. DEPARTMENT OF ENERGY
under Contract W-31-109-Eng-38

This informal report presents preliminary results of ongoing work or work that is more limited in scope and depth than that described in formal reports issued by the Energy and Environmental Systems Division.

Printed in the United States of America. Available from National Technical Information Service, U. S. Department of Commerce, 5285 Port Royal Road, Springfield, Virginia 22161.

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by

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Integrated Assessments and Policy Evaluation Group

January 1983

work sponsored by

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Air Quality Planning and Standards
Ambient Standards Branch

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ACKNOWLEDGMENT

The authors would like to thank several individuals at ANL whose assistance was particularly valuable. Dee Seymour who prepared the GROWTH programs, the inventory modification programs, and many additional programs not specifically noted in this work and who was in charge of processing, reprocessing, and re-reprocessing an endless list of scenarios, final scenarios, and latest final scenarios. Pat Juszczyk who ably assisted Dee in processing the scenarios. Elliott Levine who directed the development of the PM10 inventories and the GROWTH program. Craig Swietlik who modified his program for integrating size dependent efficiencies and particle-size distributions to suit our needs. Les Conley for developing the early plant files. Ann Smith who typed the original mattes and Barbara Salbego who loves to type equations and who was responsible for the final copy and tables. Finally, Pat Dermott for the excellent graphics.

And at EPA, our project officer, Henry Thomas, whose phone calls requesting another set of scenarios were always met with a phone call calling for additional corrections and who supported our efforts with comprehension and unflagging good humor.

The assistance of Karl Held and Mike Mochan at EEA and of Bob Horst at Mathtech is also gratefully acknowledged.

1 INTRODUCTION

This technical support document describes the analysis system used to estimate the air quality impacts and the direct industrial costs associated with implementation of alternative national ambient air quality standards for particulate matter. These results were intended to be used in support of a Regulatory Impact Analysis of the alternative standards both directly and indirectly as input data to further economic analyses and analyses of benefits. The current system is an expansion and modification of an earlier system developed by Energy and Environmental Analysis (EEA) and described in Refs. 1-3. Significant modifications of the EEA system were required in order to provide, among other things, a complete, consistent treatment of growth and retirement, a consistent treatment of area sources, and the capability to handle PM10. Both systems are implemented in a series of computer codes. The schedule for review of the alternative standards did not permit a major restructuring of the earlier system to remove all known inconsistencies. The magnitude of the modifications did, however, render much of the documentation in Refs. 1-3 inapplicable to the current system so a fairly complete description of the system is given in this document. Few references are made to the EEA documents even where no revisions have been made to the procedures presented therein.

Following the actual implementation of the system through the computer codes would provide the most detailed understanding of all the procedures and assumptions used. However, the flow of information between individual programs and the large number of data sets involved impede an understanding of the rationale behind the procedures being implemented and their relationship to the physical processes being simulated. This document emphasizes the concepts behind the design of the system. On the other hand, an understanding of the validity of the results requires some familiarity with the algorithms used. Section 1.1 introduces the conceptual system for the analysis. The computer system is introduced in Sec. 1.2. Throughout the text appropriate references are made to both systems to aid the reader in understanding the correspondence between concept and calculation.

1.1 CONCEPTS AND PROCEDURES

Figure 1.1 presents the major conceptual relationships between the principal data bases and calculations used in the analysis system. The procedure implements the sequence of steps normally followed in air quality planning for attainment of ambient standards (see, for example, Ref. 4):

- Develop data bases
  - Base-year air quality
  - Base-year emissions
  - Growth
  - Others as required
- Project future emissions
- Project future air quality by modeling
- Identify nonattainment problems
- Develop strategy
  - Available strategies
  - Model impact of strategies
  - Choose strategy meeting overall requirements.

There are many different implementations of this deceptively simple sequence of steps depending on the specific situation involved and the purpose of the analysis.

The analysis system adopts a county-by-county approach to making national estimates. Because of air quality data limitations, many counties are not analyzed. A small number of counties are divided into subcounty areas for the analysis. The following points describe the analysis system in terms of a number of logical units paralleling those general steps outlined in the previous paragraph. Reference to Fig. 1.1 shows how these units relate to the overall flow of the analysis.

1. Development of Data Bases. (Boxes 1,2,3,5, and 13 in Fig.1.1). The analysis begins with the TSP data bases from the EEA system. Based on these, estimates are made of PM10 air quality and emissions for the base year and of PM10 control efficiencies. The data bases are expanded to contain information on both TSP and PM10. Section 2 describes the procedures used to develop these data bases.

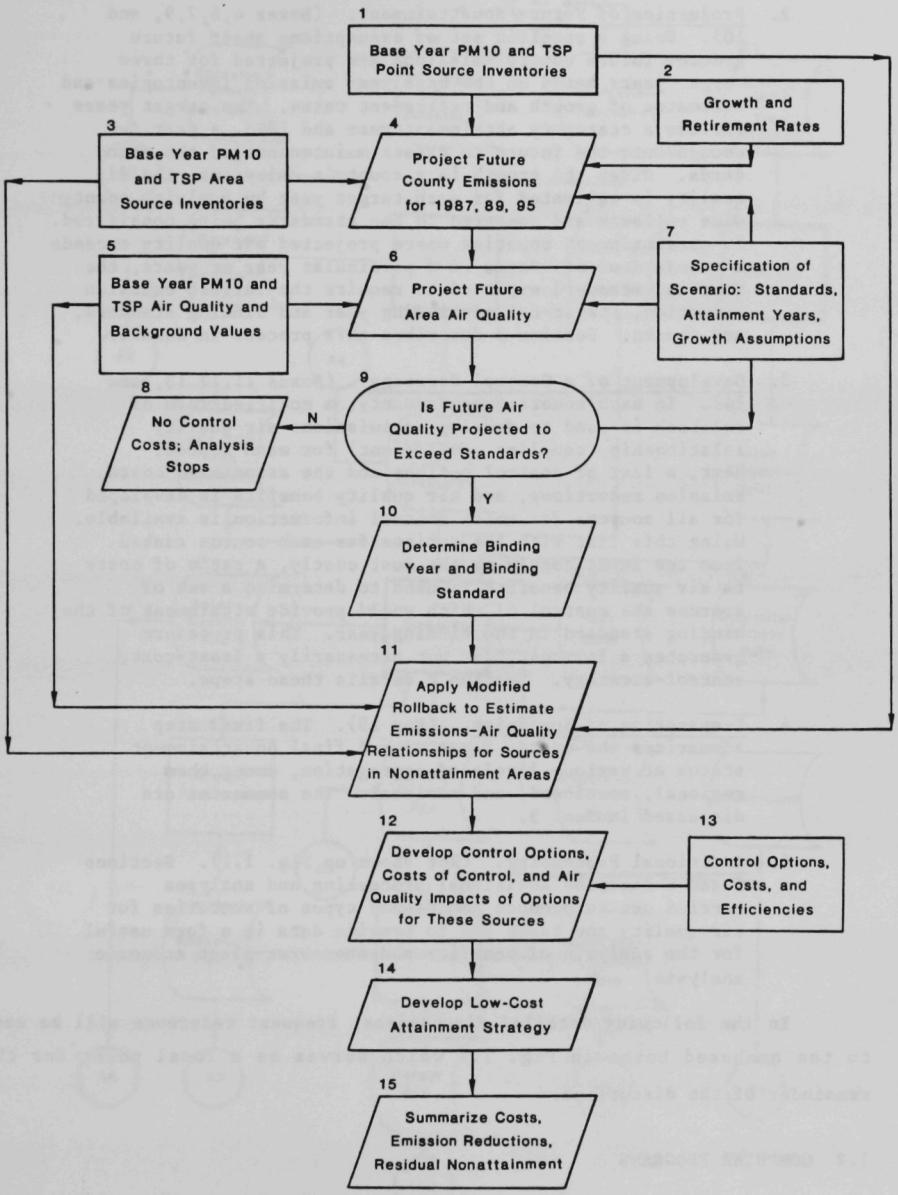

Fig. 1.1 Analytical System

2. Projection of Future Nonattainment. (Boxes 4,6,7,9, and 10). Using a specific set of assumptions about future growth, future county emissions are projected for three target years based on the base year emission inventories and estimates of growth and retirement rates. The target years include a statutory attainment year and 1995, a year far enough into the future to assess maintenance of the standards. Given the growth in a county's emissions, the air quality is estimated for each target year by applying county-wide rollback and compared to the standards being considered. In nonattainment counties where projected air quality exceeds a standard or standards in a particular year or years, the year and standard expected to require the largest emission reduction, the so-called binding year and binding standard, are chosen. Section 3 describes this process in detail.

3. Development of a Control Strategy. (Boxes 11,12,13, and 14). In each nonattainment county, a modified form of rollback is used to develop an emissions-air quality relationship (coupling coefficient) for each source. Next, a list of control options and the associated costs, emission reductions, and air quality benefits is developed for all sources for which control information is available. Using this list with the options for each source ranked from the least costly to the most costly, a ratio of costs to air quality benefits is used to determine a set of sources the control of which would provide attainment of the binding standard in the binding year. This procedure generates a low-cost, but not necessarily a least-cost, control strategy. Section 4 details these steps.

4. Preparation of Summaries. (Box 15). The final step summarizes the costs, impacts, and final nonattainment status at various levels of aggregation, among them regional, sectional, and national. The summaries are discussed in Sec. 5.

5. Additional Processing. (Not shown on Fig. 1.1). Sections 5 and 6 describe additional processing and analyses carried out to produce additional types of summaries for air quality and costs and to provide data in a form useful for the analysis of benefits and the worst-plant economic analysis.

In the following detailed discussions, frequent reference will be made to the numbered boxes in Fig. 1.1 which serves as a focal point for the remainder of the discussion.

1.2 COMPUTER PROGRAMS

The computer system is outlined in the flowcharts, Figs. 1.2A, 1.2B, and 1.2C. Descriptions of the data files are given in Table 1.1 and are cross

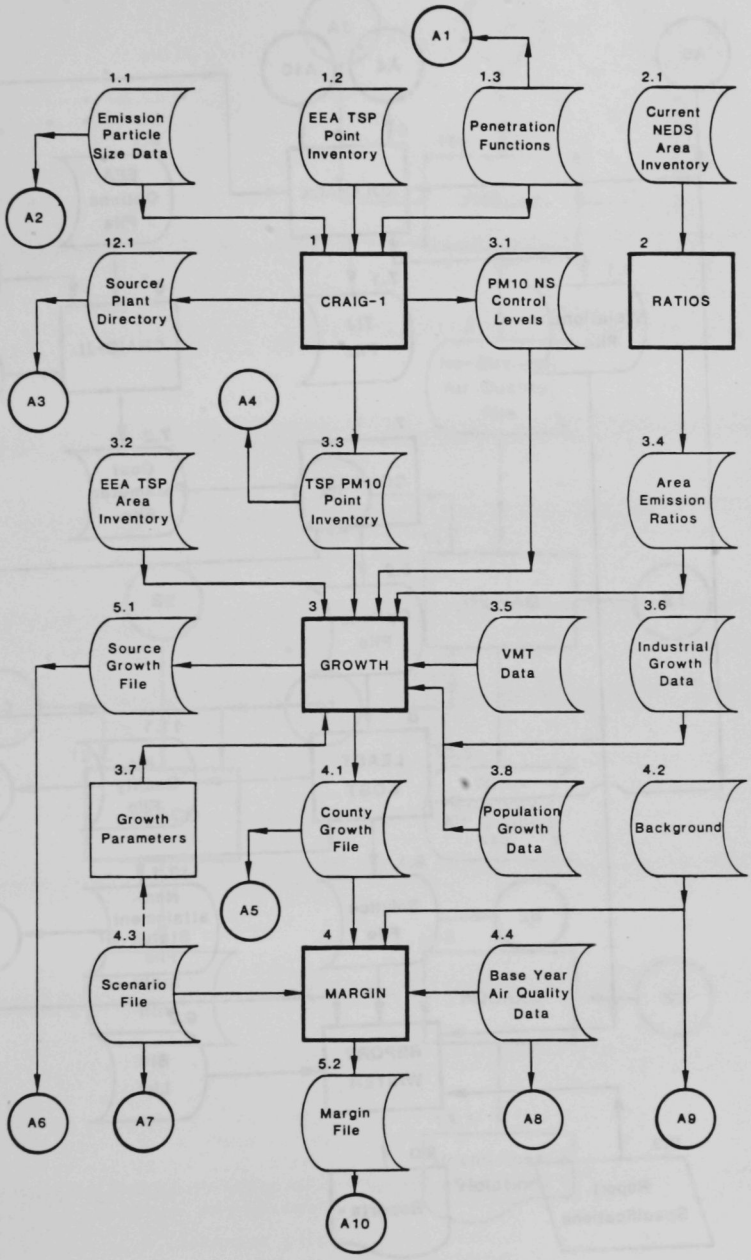

Fig. 1.2A Computer System

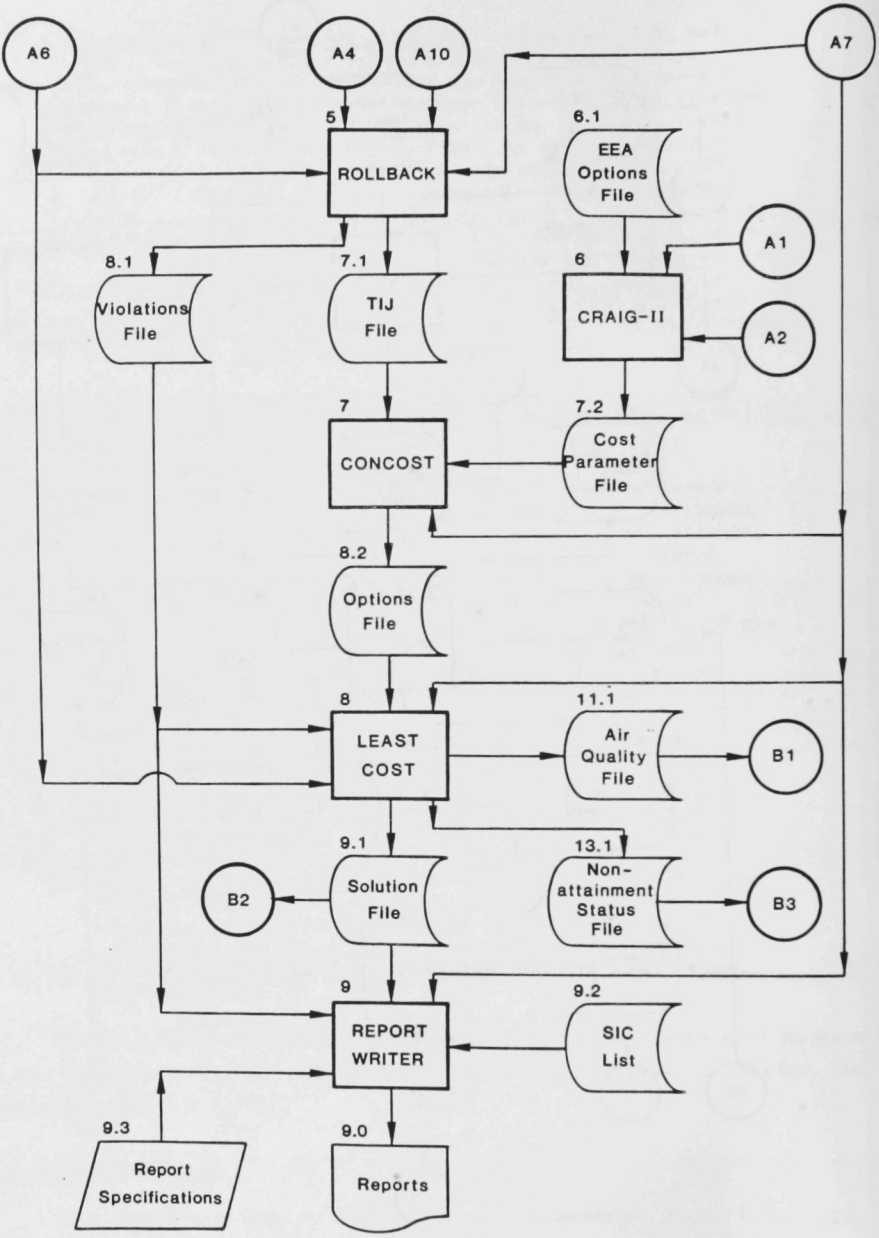

Fig. 1.2B Computer System (Cont'd)

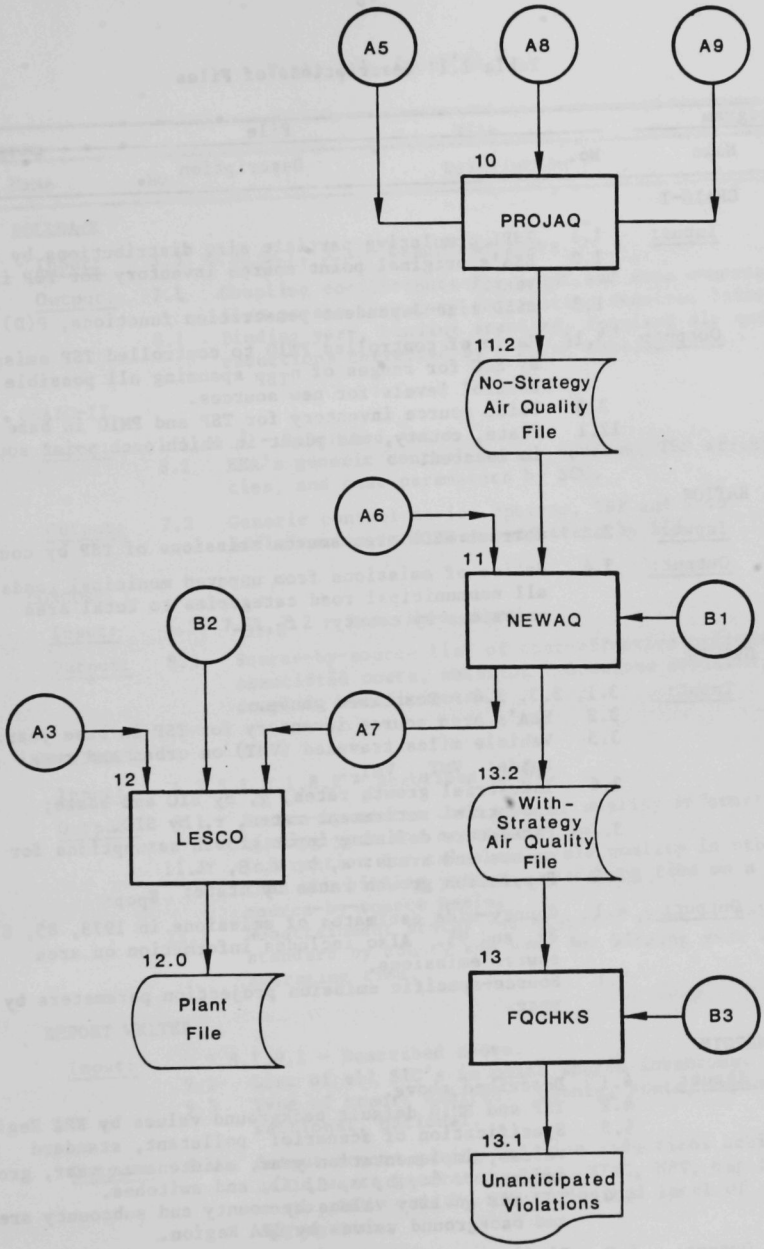

Fig. 1.2C Computer System (Cont'd)

Table 1.1 Descriptions of Files

Program No.	Program Name	File No.	File Description
1	CRAIG-I		
	Input:	1.1	IERL cumulative particle size distributions by SCC.
		1.2	EEA's original point source inventory for TSP in base year.
		1.3	ESED size-dependent penetration functions, P(D).
	Output:	3.1	Ratio of controlled PM10 to controlled TSP emissions by SCC for ranges of η_{TSP} spanning all possible control levels for new sources.
		3.3	Point source inventory for TSP and PM10 in base year.
		12.1	State, county, and plant in which each point source is located.
2	RATIOS		
	Input:	2.1	Current NEDS area source emissions of TSP by county.
	Output:	3.4	Ratios of emissions from unpaved municipal roads and all nonmunicipal road categories to total area emissions by county: f_U, f_O.
3	GROWTH		
	Input:	3.1, 3.3, 3.4	- Described above.
		3.2	EEA's area source inventory for TSP in base year.
		3.5	Vehicle miles traveled (VMT) on urban and rural roads: VMT_u, VMT_r.
		3.6	Industrial growth rates, g, by SIC and state; industrial retirement rates, r, by SIC.
		3.7	Parameters defining input growth assumptions for points and areas: a, b, α, β, γ.
		3.8	Population growth rates by state: g_{pop}.
	Output:	4.1	County-wide estimates of emissions in 1978, 85, 87, 89, and 95. Also includes information on area source emissions.
		5.1	Source-specific emission projection parameters by year.
4	MARGIN		
	Input:	4.1	Described above.
		4.2	TSP and PM10 default background values by EPA Region.
		4.3	Specification of scenario: pollutant, standard values, implementation year, maintenance year, growth parameters (a, b, α, β, γ), and switches.
		4.4	TSP air quality values by county and subcounty area and background values by EPA Region.
	Output:	5.2	Binding year, binding standard, required air quality reductions.

Table 1.1 (Cont'd)

Program		File	
No.	Name	No.	Description
5	ROLLBACK		
	Input:	3.3, 4.3, 5.1, 5.2 - Described above.	
	Output:	7.1	Coupling coefficients for point and area sources. Also passes inventory information required later.
		8.1	Binding year, binding standard, required air quality reductions corrected by 1 $\mu g/m^3$ cutoff.
6	CRAIG-II		
	Input:	1.1, 1.3 - Described above.	
		6.1	EEA's generic control device options, TSP efficiencies, and cost parameters by SCC.
	Output:	7.2	Generic control device options, TSP and PM10 efficiencies, and cost parameters by SCC.
7	CONCOST		
	Input:	4.3, 7.1, 7.2 - Described above.	
	Output:	8.2	Source-by-source list of cost-effective options, associated costs, emission reductions achieved, and coupling coefficients.
8	LEASTCOST		
	Input:	4.3,5.1,8.1,8.2 - Described above.	
	Output:	9.1	Source-by-source cost and air quality information for binding year and averaging time.
		11.1	Information for calculating air quality in other than the binding year and averaging time on a source-by-source basis.
		13.1	Nonattainment status and distance above or below standard by county and area for binding year and averaging time.
9	REPORT WRITER		
	Input:	4.3,8.1,9.1 - Described above.	
		9.2	List of all SIC's in point source inventory.
		9.3	Type of report desired: county, state, regional, sectional, national.
	Output:	9.0	Output report giving emission reductions achieved, solid waste generated, ATAC, BTAC, NPV, capital costs, O&M costs by SIC at desired level of aggregation.

Table 1.1 (Cont'd)

Program		File	
No.	Name	No.	Description
10	PROJAQ		
	Input:	4.1,4.2,4.4 - Described above.	
	Output:	11.2	Projected air quality assuming no strategy was applied by county and area.
11	NEWAQ		
	Input:	4.3,5.1,11.1,11.2 - Described above.	
	Output:	13.2	Projected air quality with control strategy applied by county and area.
12	LESCO		
	Input:	4.3,9.1,12.1 - Described above.	
	Output:	12.0	Cost information on a plant-by-plant basis for certain specified SIC's.
13	FQCHKS		
	Input:	13.1,13.2 - Described above.	
	Output:	13.0	List of areas where nonattainment is projected for other than binding year or averaging time.

referenced by number to Fig. 1.2. Figures 1.2A and B cover the programs needed to produce the basic reports on industrial costs and air quality. Figure 1.2C covers additional programs needed to support the economic and benefits analysis. Additional programs for air quality have not been shown. The sequence of programs GROWTH, MARGIN, ROLLBACK, CONCOST, and LEASTCOST was taken from the earlier EEA model and modified for this work. In general terms, GROWTH projects future county emissions in accordance with input assumptions defining a specific scenario and based on the inventoried emissions. MARGIN uses these estimates to project future air quality, compares that air quality to the standards specified in the scenario, determines the extent of nonattainment, if any, and chooses the binding year and binding standard in nonattainment areas. ROLLBACK calculates source-specific coupling coefficients for use in developing control options and passes along information defining the extent of the nonattainment problems. CONCOST produces a list of cost-effective control options for each source along with the

associated emission reductions and source-specific costs. LEASTCOST chooses a strategy by applying the available options to attain the binding standard in the binding year. Thus, the main sequence of programs is seen to correspond fairly closely to the conceptual scheme of Sec. 1.1. Table 1.2 provides the correspondence between the programs from CRAIG-I through the REPORT WRITER, that is, from the modification of the earlier EEA inventories through production of summary cost and air quality information. Figure 1.2 will also be referred to frequently in the following detailed discussions.

Table 1.2 Correspondence between Programs and Conceptual Flow

Box in Fig. 1.1	Program in Fig. 1.2A, B, C
1	CRAIG-I
2	Data sets
-	RATIOS[a]
3,4	GROWTH
5	Data sets
7	Data set
6,8,9,10	MARGIN
11	ROLLBACK
12	CONCOST
13	CRAIG-II
14	LEASTCOST
15	REPORT WRITER

[a]Provides data required by GROWTH to modify area source inventory.

2 DATA BASES

This section describes the data bases used in the analysis for air quality, emissions, and direct costs. Since the availability of air quality data determines the set of counties actually analyzed, this data base is discussed first, followed by discussions of the emissions inventory and cost data bases. Throughout, the emphasis is on the changes made in the data bases, particularly those required to treat particulate matter less than 10 μm (PM10). The original EEA data bases are described more fully in Refs. 2 and 3.

2.1 AIR QUALITY DATA BASE

This data base corresponds to box 5 in Fig. 1.1 and files 4.2 and 4.4 in Fig. 1.2A.

Base Year TSP Data. The base-year air quality data was obtained from a TSP data base assembled by EEA as described in Ch. 4 of Ref. 3. In developing this data base, TSP concentration values were taken from several sources. In order of precedence these were:

1. The design value used in the development of the control strategy in the revised 1979 SIP;
2. The value used to determine an area's attainment status; or
3. The highest monitored readings for the area in 1977 and 1978 or back to 1975 if valid data for the preferred years was unavailable.

Both monitored and modeled values were taken from the SIPs. Monitored values for the third level data source were taken from EPA's Storage and Retrieval of Aerometric Data (SAROAD) system after screening for validity. If no data was found for a designated attainment area at any of the three levels, the area was dropped from the analysis. No data was found for 23 designated nonattainment areas and a value 1 $\mu g/m^3$ above the appropriate standard was used in the TSP data file.

Because of the differing forms of the existing and alternative standards, four base-year values were required for each area: an annual geometric

mean (AGM), an observed 24-hour value (OB24), an annual arithmetric mean (AAM), and 24-hour expected value (EX24). To be included in the analysis, an area had to have a valid annual geometric mean and/or a valid 24-hour observed value available from one of the data sources. Arithmetic means were also frequently available. However, expected 24-hour concentrations were not available and were calculated from the available data by EPA's Monitoring and Data Analysis Division (MDAD) except for areas with modeled data for which the EX24 value was set equal to the OB24 value.

In some areas, the base year values were not consistent with the designations of attainment status in the Federal Register. In cases of conflict, the base-year value was changed by replacing the original value with a new value from SAROAD or arbitrarily replacing it with a value near the appropriate standard. For example, a county designated as primary nonattainment for both TSP standards but whose base-year values were below the primary standards of 75 and 260 $\mu g/m^3$ would have values 1 $\mu g/m^3$ higher than the standards, that is, 76 and 261 $\mu g/m^3$, substituted for the original values for the AGM and OB24, respectively.* Such resolutions were required in 412 counties.

The assembly of the original data set frequently led to several areas having the same base-year air quality, probably where values in one area were used to determine attainment status or to develop SIPs in other neighboring areas. In one instance 12 counties in California had identical, very high base-year values which led to significant residual nonattainment. For this group of counties values from SAROAD were supplied by EPA and substituted for the values in the EEA file for use in this work; no adjustments were made for other similar groups of areas.

This data base for base-year TSP air quality corresponds to box 4.4 in Fig. 1.2A.

Missing Base-Year Values. Not all four base-year values were available for every area. Missing values were filled in by the use of regression equations. Rather than add values obtained by regression to the data base, substitution of missing values was effected operationally when future air

*Chapter 4 in Ref. 2 contains a complete list of the defaults used to resolve such inconsistencies.

quality was projected in MARGIN. The regression was carried out using all appropriate pairs of TSP air quality values.* To produce complete sets of air quality data, regressions would have had to have been applied in 227 areas. For a particular scenario, air quality estimates based on regressions would be used in only a fraction of this number of areas. The equations used are presented in Table 2.1 along with several regression statistics. With the large number of points involved all the regressions are significant at far greater than the 99% confidence level. Still only 65% of the variation is explained by the regressions for GEOA and OB24. Given that values just above or at the TSP standards had been substituted into the data base prior to development of the regression equations, an attempt was made to screen out those values which were not based on actual measurements of TSP concentrations. Unfortunately, the substituted values had not been labeled as distinct from measured values in the data base. Individual data sets with GEOA = 60, 61, 75, or 76 $\mu g/m^3$ or OB24 = 150, 151, 260, or 261 $\mu g/m^3$ were not included in the regression even though this may have excluded some legitimate, measured sets.

When missing values were encountered for a particular area, it was required that there be either a valid annual geometric mean (GEOA) or a valid observed 24-hour value (OB24) in order to apply the regression equations. Other regression equations could have been used to, for example, estimate geometric means from arithmetic means but the process used, relying on data corresponding to the form of the current TSP ambient standards, was considered to utilize the best data. It should be noted that the procedure used here makes no distinction between measured and modeled values for OB24 and that two regression equations might be applied to calculate some missing values. For example, in an area whose only valid data was an observed 24-hour value (OB24), the arithmetic mean (ARITHA) would be calculated from the geometric mean (GEOA); see Eq. 3 in Table 2.1. The value of GEOA itself would be calculated from the OB24 value by means of Eq. 1 in Table 2.1.

All told, base year TSP data was available for 1231 counties or county-equivalents containing 1259 analysis areas.

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*The regression programs are not represented in Fig. 1.2 because the regression equations were contained in the MARGIN code.

Table 2.1 Regression Equations for Air Quality Data

No.	Equation	r^2	Independent Variable		Dependent Variable		No. of Points
			Average	Standard Deviation	Average	Standard Deviation	
1	GEOA = 21.86 + 0.250 (OB24)	0.650	151.59	90.17	59.82	28.00	910
2	OB24 = -3.77 + 2.60 (GEOA)	0.650	59.82	28.00	151.59	90.17	910
3	ARITHA = 2.24 + 1.11 (GEOA)	0.925	59.07	27.43	67.79	31.66	885
4	EX24 = -13.99 + 3.79 (GEOA)	0.925	67.79	31.66	59.07	27.43	885

TSP Background. Annual and 24-hour TSP background levels were included in the EEA data when available. Values were available for about 95 counties and were usually taken from the applicable SIP.[2] In the remainder of the areas, default annual backgrounds were used. These values were based on Regional averages of nonurban/rural monitoring sites and were used as both annual and 24-hour estimates of background. For Alaska and Hawaii, state-specific values of background were used.[2] The TSP background file is file 4.2 in Fig. 1.2A.

PM10 Concentrations. Estimates of PM10 concentration (χ_{10}) were made by applying a single conversion factor to the TSP concentrations (χ_{TSP})

$$\chi_{10} = 0.55\chi_{TSP}. \qquad (2.1.1)$$

Operationally, the conversion was effected in the MARGIN program so a file of base year PM10 air quality data was never actually developed. The factor of 0.55 was provided by the scenario file (file 4.3) in order to provide the capability of using other factors. The factor of 0.55 was obtained from EPA and was based on analysis of data from EPA's dichotomous sampler network and distributions of ambient particle sizes. The dichotomous sampler network provides data from side-by-side high volume samplers for TSP and dichotomous samplers with a 15 m cut point. Equation 2.1.1 was applied to all TSP concentrations regardless of averaging time or type of average.

The base year PM10 air quality was assumed to be related to the TSP air quality of the same averaging time and type of average by means of Eq. 2.1.1. For example, if a particular PM10 alternative was specified in terms of an annual arithmetic mean and a 24-hour expected value, the PM10 design values were calculated from the annual arithmetic mean TSP value and 24-hour expected TSP value by multiplication by 0.55. The same factor was also applied to TSP background values and to the Regional defaults to estimate PM10 background values.

2.2 EMISSIONS DATA BASE

This section describes the development of the emission data bases corresponding to boxes 1 and 3 in Fig. 1.1. EEA developed point source and area source inventories for TSP emissions as described in Refs. 2 and 3. These inventories were nominally representative of 1978 emission levels. Sections 2.2.1 and 2.2.2 describe these inventories for points and areas,

respectively, and the development of inventories for PM10 from them. Inventories were only developed for counties having base-year air quality data. Emissions totals for TSP and PM10 in the base year (1978) are given in Table A.1 in Appendix A.

2.2.1 Point Source Emission Inventory

TSP Inventory. Briefly, the TSP point source inventory prepared by EEA[2] was based on information available in EPA's National Emissions Data System (NEDS) as updated by the Compliance Data System (CDS). Small sources emitting less than 5 tons per year were screened out of the analysis as were sources with invalid stack parameters and/or invalid operating parameters in cases where appropriate defaults could not be provided. Screening out the small sources aided in keeping the inventory managable by reducing the number of sources from about 217,000 to about 37,000 while resulting in the loss of under 2% of the TSP emissions from point sources. In addition, some 8,000 sources of nontraditional fugitive emissions from utility and selected industrial storage piles, paved plant roads, and unpaved plant roads were added to the inventory. The estimates of plant fugitive emissions were made by applying a model plant concept.[3]

Although nontraditional fugitives were added to the inventory, the status of the traditional industrial process fugitive particulate emissions (IPFPE) is by no means clear. IPFPE emissions are not a part of the NEDS system of estimating emissions. They may be included in information sent to NEDS by some states and not included by other states. There is no easy way to determine the extent of the problem posed by the unknown status of IPFPE emissions; these emissions were not analyzed as a separate controllable category in this work. To the extent that these emissions were included in the inventoried emission rates, they would be treated as stack emissions, confined at the point of generation and easily ducted to a collector. Since IPFPE's generally require hooding or expensive capture systems of relatively low-efficiencies, frequently well under 90%, the overall collection efficiency would generally be overestimated and the control costs under-estimated by including them with the stack emissions. To the extent that IPFPE's were not included in the inventoried rates, the air quality impact of sources with large IPFPE components may have been underestimated, because these emissions are frequently emitted near ambient temperatures at low levels from roof monitors or similar openings.

The TSP inventory as developed by EEA was retained for this work. To treat PM10, it was necessary to develop a PM10 emissions inventory. Different estimating procedures were used for nontraditional fugitives and for processes. Emission factors for PM10 are not readily available for most processes and a more complicated procedure for estimating PM10 emissions was required than the familiar one of multiplying an operating rate by a general emission factor. The following subsections describe the procedure used for nontraditional fugitive emissions and then, beginning with a short theoretical development, the procedure and data bases used for process emissions.

Nontraditional Fugitive Emissions of PM10. Ratios of PM10 to TSP emissions for the four classes of nontraditional fugitive emissions (NTF) were estimated from the literature. Estimates of PM10 emissions were made by

$$PM10_{NTF} = R \times TSP_{NTF}$$

where R is the ratio estimated from the literature, TSP_{NTF} is the inventoried nontraditional fugitive emissions for TSP, and $PM10_{NTF}$ is the corresponding estimate for PM10. Table 2.2 lists the ratios used. In developing these ratios, particle masses were assumed to follow a log-normal distribution.

Emissions of PM10 from Processes. Assume that the following information is available for a source as a function of particle diameter D in μm:

$\hat{S}(D)$ = normalized uncontrolled mass distribution of particles by size for the source, and

Table 2.2 Conversion Factors for Nontraditional Fugitive Emissions

Nontraditional Fugitive Source	Conversion Factor (PM10/TSP)
Boiler storage piles[a]	1.0
Process storage piles[a]	1.0
Paved plant roads[b]	0.6
Unpaved plant roads[b]	0.46

[a]Based on Ref. 5.

[b]Based on Ref. 6

$\eta_1(D)$ and $\eta_2(D)$ = control efficiencies of the particle collectors used to control the source.

Further assume that both

TSP^A_{ctr} = actual controlled TSP emissions, and

TSP^A_{unc} = actual uncontrolled TSP emissions

are known. TSP^A_{ctr} and TSP^A_{unc} are available in the TSP inventory along with an overall control efficiency for TSP and a specification of the type of process and the types of TSP control devices used.

Since the distribution is normalized

$$\int_0^\infty S(D)dD = 1 \qquad (2.2.1)$$

and

$$\int_{D_1}^{D_2} \hat{S}(D)dD = \text{the fraction of particle mass in the size range } D_1 \leq D \leq D_2. \qquad (2.2.2)$$

In particular,

$$\int_{0.1}^{100} \hat{S}(D)dD = \text{the fraction of total uncontrolled particle emissions that are TSP} \qquad (2.2.3)$$

where TSP has been defined as particles in the size range from 0.1 to 100 μm (see 40CFR50; 36FR22,384 et seq.). Assuming the same lower cutoff for PM10, PM10 would be defined as particles in the 0.1 to 10 μm size range and

$$\int_{0.1}^{10} \hat{S}(D)dD = \text{the fraction of total uncontrolled particle emissions that are PM10.} \qquad (2.2.4)$$

For a given set of collectors, the fraction of the total uncontrolled particle mass emitted in the size range from D_1 to D_2 is

$$\int_{D_1}^{D_2} P_1(D)P_2(D)\hat{S}(D)dD \qquad (2.2.5)$$

where allowance has been made for two particulate collectors in series with penetrations

$$P_1(D) = [1 - \eta_1(D)/100] \tag{2.2.6}$$

and

$$P_2(D) = [1 - \eta_2(D)/100]. \tag{2.2.7}$$

P_1 and P_2 are pentration functions giving the throughput, that is, the fraction of input loading actually emitted, by their respective collectors and $\eta_1(D)$ and $\eta_2(D)$ are the corresponding efficiencies.

To apply Eqs. 2.2.3 and 2.2.5, the total emissions of the source over the size range $0 \leq D \leq \infty$ would need to be known. However, the only inventoried values are for the restricted size range corresponding to TSP and it is convenient to define a normalized TSP size distribution S(D) by

$$S(D) = \frac{\hat{S}(D)}{\int_{0.1}^{100} \hat{S}(D)dD}, \quad 0.1 \leq D \leq 100. \tag{2.2.8}$$

With this definition,

$$\int_{0.1}^{100} S(D)dD = 1. \tag{2.2.9}$$

Then the mass fraction of total uncontrolled TSP emissions less than a given size D is

$$U(D) = \int_{0.1}^{D} S(D)dD \tag{2.2.10}$$

and the emitted mass fraction of total uncontrolled TSP emission less than a given size D is

$$C(D) = \int_{0.1}^{D} P_1(D)P_2(D)S(D)dD. \tag{2.2.11}$$

Equations 2.2.10 and 2.2.11 are only defined for values of D for which $0.1 \leq D \leq 100$. It should be noted that $C(.1) = U(.1) = 0$ and that $U(100) = 1$. Also, $C(D) = U(D)$ only when $P_1(D') = 1 = P_2(D')$ for all D' such that $0.1 \leq D' \leq D$, that is, if $\eta_1(D') = 0 = \eta_2(D')$ for all D' in the range from 0.1 to D.

With these definitions of C(D) and U(D) as fractions of uncontrolled TSP emissions, the theoretical uncontrolled and controlled emission rates of

particles in the size range from 0.1 to D, $Q_u^T(D)$ and $Q_c^T(D)$, respectively, may be calculated from

$$Q_u^T(D) = TSP_{unc}^A \times U(D) \tag{2.2.12}$$

and

$$Q_c^T(D) = TSP_{unc}^A \times C(D). \tag{2.2.13}$$

Also, a theoretical control efficiency, H(D), for particles larger than 0.1 μm but smaller than D can be found by noting that

$$H(D) = \frac{Q_u^T(D) - Q_c^T(D)}{Q_u^T(D)} \times 100$$

$$= \left[1 - \frac{C(D)}{U(D)}\right] \times 100. \tag{2.2.14}$$

The theoretical control efficiency for TSP (particles in the range between 0.1 and 100 μm) is simply

$$H(100) = [1 - C(100)] \times 100 \tag{2.2.15}$$

and the theoretical control efficiency for PM10 (particles in the range between 0.1 and 10 μm) is

$$H(10) = \left[1 - \frac{C(10)}{U(10)}\right] \times 100. \tag{2.2.16}$$

There is no reason to expect that H(100) would be equal to the inventoried efficiency η_{TSP}. An adjustment is necessary to ensure consistency and physical plausibility, to ensure, for example, that emissions of PM10 are less than emissions of TSP. The approach chosen here was to renormalize the function C(D) defined in Eq. 2.2.11 by a factor ω and to calculate a renormalized theoretical TSP efficiency $H_R(100)$. Defining the renormalized $C_R(D)$ by

$$C_R(D) = \omega C(D), \tag{2.2.17}$$

the consistency condition requires that

$$\eta_{TSP} = H_R(100) = [1 - \omega C(100)] \times 100. \tag{2.2.18}$$

Therefore,

$$\omega = \frac{1}{C(100)}\left[1 - \frac{\eta_{TSP}}{100}\right] \tag{2.2.19}$$

from which it can be shown that ω is simply the ratio of the actual throughput to the theoretical throughput before renormalization:

$$\omega = \frac{\left[1 - \frac{\eta_{TSP}}{100}\right]}{\left[1 - \frac{H(100)}{100}\right]} . \qquad (2.2.20)$$

In this formulation, ω has the physical interpretation of an adjustment to the penetration curves in Eq. 2.2.11 to account for variation between different collectors and sources of particular generic types. Renormalized controlled emissions can then be found from

$$Q_c^R(D) = TSP_{unc}^A \times C_R(D). \qquad (2.2.21)$$

Note that

$$\begin{aligned} Q_c^R(100) &= TSP_{unc}^A \times C_R(100) \\ &= TSP_{unc}^A \times \omega C(100) \\ &= TSP_{unc}^A \times \frac{1}{C(100)} \left[1 - \frac{\eta_{TSP}}{100}\right] \times C(100) \\ &= TSP_{unc}^A \left[1 - \frac{\eta_{TSP}}{100}\right] \\ &= TSP_{ctr}^A \end{aligned} \qquad (2.2.22)$$

maintaining consistency with the inventory.

Operationally, the emission inventory provided: 1) estimates of controlled and uncontrolled TSP emissions, TSP_{ctr}^A and TSP_{unc}^A, respectively, 2) a specification of the type of control devices from which generic estimates of $P_1(D)$ and $P_2(D)$ could be made, 3) the overall TSP control efficiency η_{TSP}, and 4) a specification of the type of process from which $\hat{S}(D)$ could be estimated. In this work the cut points of interest were D = 100 μm for TSP and D = 10 μm for PM10 and the estimation of emissions proceeded as follows:

1. Calculate $Q_u^T(10)$, $Q_u^T(100)$, $Q_c^T(10)$, and $Q_c^T(100)$ from Eqs. 2.2.12 and 2.2.13 using Eq. 2.2.8 to define S(D) and Eqs. 2.2.10 and 2.2.11 to define U(D) and C(D).
2. Calculate ω using Eq. 2.2.19.

3. Calculate the renormalized factors $C_R(10)$ and $C_R(100)$ using Eq. 2.2.17.
4. Calculate $Q_c^R(10)$ and $Q_c^R(100)$ from Eq. 2.2.21.
5. Calculate a renormalized control efficiency for PM10 from $\eta_{PM10} = H_R(10) = [1 - \omega C(10)/U(10)] \times 100$ applying the renormalization factor in Eq. 2.2.16 for PM10.

This procedure gives the uncontrolled TSP emission rate $Q_u^T(100) = TSP_{unc}^A$, the controlled TSP emission rate $Q_c^R(100) = TSP_{ctr}^A$, and estimates of the uncontrolled and controlled PM10 emissions that are always less than the corresponding TSP emissions. The calculational procedures just described are contained in the computer code CRAIG-I in Fig. 1.2A. CRAIG-I was actually several codes shown as a single box in the figure for simplicity. All versions of CRAIG were based upon the approach just presented; the version of interest at this point calculated the parameters needed for the PM10 point source inventory (file 3.3) based on the EEA inventory (file 1.2) and information from files 1.1 and 1.3 relating to the particle size distributions and penetration functions.

To make the process somewhat clearer, Fig. 2.1 summarizes the steps for a single source. The calculational procedure just described covers boxes 13-18 in the figure. The remaining boxes show the flow of information from the inventory and other required data sets. The following subsections describe the particle size distributions (box 13) and the penetration functions (box 9) required as inputs to the calculation of PM10 emissions and efficiencies.

Particle Size Distributions. This subsection describes the data used to estimate the particle size distributions S(D) and basically related to boxes 8,11,12, and 13 in Fig. 2.1 and file 1.1 in Fig. 1.2A. EPA's Industrial Environmental Research Laboratory (IERL) provided information giving the cumulative percentage of total emissions mass associated with particles less than 15 m and less than 2.5 m for various types of sources. The source type was specified by an 8-digit Source Classification Code (SCC) which was also available for the point sources in the inventory making it possible to match the sources with the IERL data. Some assumptions were required to use the IERL data which only gave two points in the entire distribution. In consultation with EPA, it was decided to assume that a log-normal distribution would adequately describe the particle size distribution. Given the IERL data, the form of the distribution could be derived fairly easily.[7] Figure 2.2

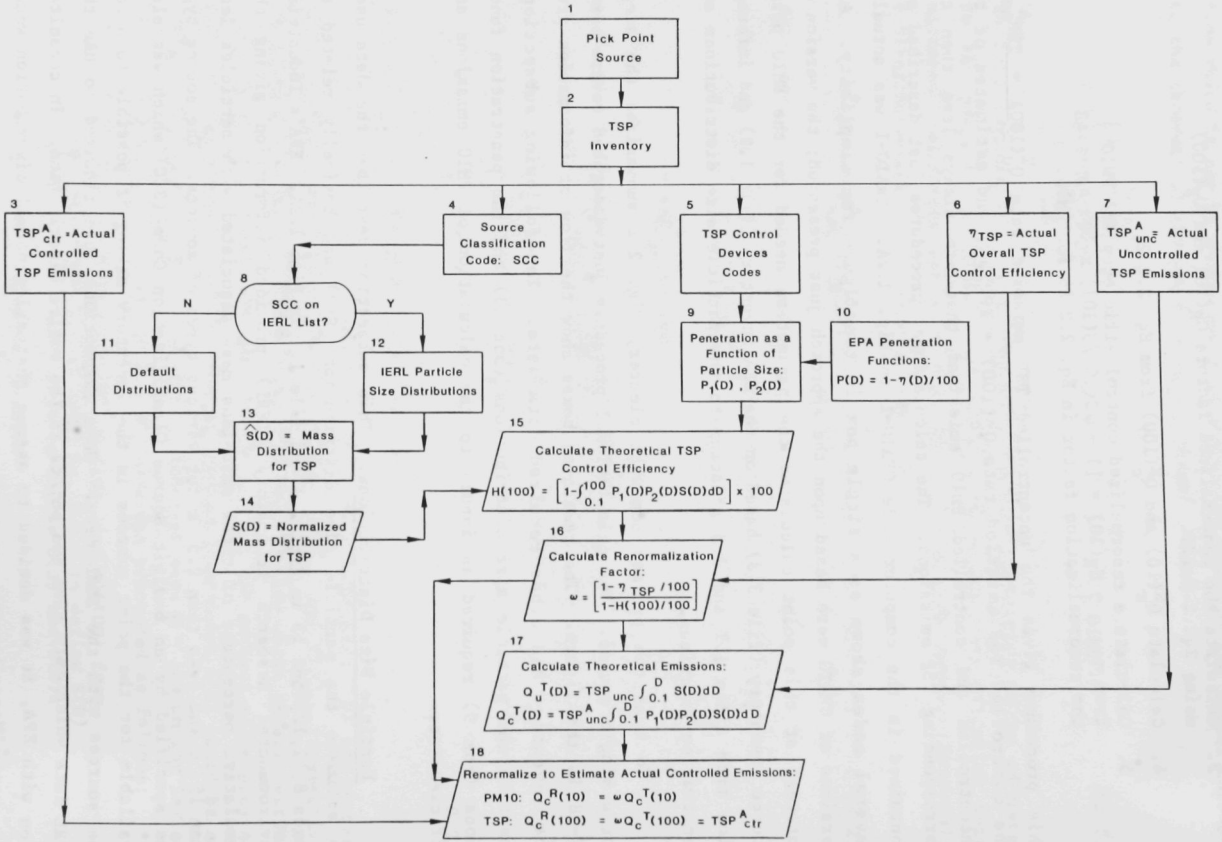

Fig. 2.1 Estimation of Point Source Emissions

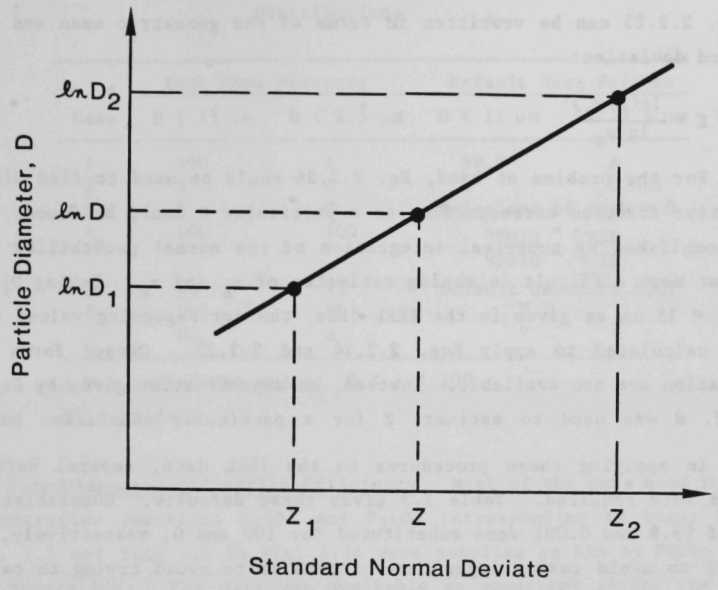

Fig. 2.2 Cumulative Log-Normal Frequency Distribution

represents a lognormal distribution as it appears plotted on log-probability paper. The plot is a straight line. In terms of the standard normal deviate, the equation of the line is

$$Z = Z_1 + \frac{\ln(D/D_1)}{\ln s_g} \tag{2.2.23}$$

where

$$\ln s_g = \frac{\ln(D_2/D_1)}{Z_2 - Z_1} \tag{2.2.24}$$

defines the geometric standard deviation of the distribution. The geometric mean of the distribution (m_g) has a normal deviate Z = 0. Taking Z = 0 and D = m_g in Eq. 2.2.23, we find

$$m_g = \frac{D_1}{s_g^{Z_1}} \tag{2.2.25}$$

and Eq. 2.2.23 can be rewritten in terms of the geometric mean and geometric standard deviation:

$$Z = \frac{\ln(D/m_g)}{\ln s_g} \qquad (2.2.26)$$

For the problem at hand, Eq. 2.2.26 could be used to find S(D) if the cumulative fraction corresponding to a particular Z could be found. This can be accomplished by numerical integration of the normal probability function. Somewhat more difficult is making estimates of s_g and m_g. Taking D_1 = 2.5 μm and D_2 = 15 μm as given in the IERL data, the corresponding values of Z need to be calculated to apply Eqs. 2.2.24 and 2.2.25. Closed forms for this calculation are not available. Instead, an approximation given by Eq. 26.2.23 in Ref. 8 was used to estimate Z for a particular cumulative percentage.

In applying these procedures to the IERL data, several default procedures were required. Table 2.3 gives these defaults. Cumulative percentages of 99.9 and 0.001 were substituted for 100 and 0, respectively, in cases 1 and 2 to avoid taking logarithms of zero or to avoid trying to calculate a value of Z equal to infinity. Case 3 implies that all emissions are larger than 15 μm in size and hence fall beyond the size range associated with PM10. Controlled and uncontrolled emissions of PM10 were set equal to zero. In case 4, all particles are less the 2.5 μm in size and hence TSP and PM10 are identical. Thus, the inventoried controlled and uncontrolled TSP emissions and TSP control efficiency should also apply to PM10. In cases 5,6,7 sufficient information does not exist to either estimate the distribution or to provide defaults for the desired end products of the calculation. In these cases, the default distributions described below were applied and the IERL data was ignored.

Information was not available in the IERL data for all the SCC's in the inventory. For such SCC's and for IERL distributions which were unusable (cases 5,6, and 7 in Table 2.3) two default distributions were developed, one for combustion sources with SCC's beginning with 1 or 2 and one for process sources with SCC's beginning with a 3. A default cumulative percentage was chosen at 2.5 μm and at 15 μm for each default distribution. The median cumulative percentage for SCC's with available data was chosen for the default value. When unusable data or no data was found in the IERL information, the two appropriate medians were chosen to define the particle size distribution.

Table 2.3 Defaults for IERL Particle Size Distributions

Case	IERL Mass Percents		Default Mass Percent	
	D < 15 μm	D < 2.5 μm	D < 15 μm	D < 2.5 μm
1	100	A	99.9	A
2	A	0	A	0.001
3	0	0	Emissions of PM10 = 0.	
4	100	100	$\eta_{PM10} = \eta_{TSP}$ $Q_{PM10} = Q_{TSP}$	
5	ND	<1	Default based on SCC.	
6	ND	ND	"	
7	ND	A	"	

A = A legitimate value: $0 < A < 100$.

ND = No data.

Size-Dependent Collection Efficiency. Most of the data used to provide the penetration functions $P_1(D)$ and $P_2(D)$ corresponding to boxes 9 and 10 in Fig. 2.1 and file 1.3 in Fig. 1.2A were supplied to EPA by PEDCo Environmental Specialists.* The data was available as equations giving the penetration as a function of particle size for particles between 0.1 and 15 μm. Table 2.4 gives the EPA penetration functions and the device codes associated with them for purposes of this work. The inventory contained NEDS control device codes and these were matched to the penetration curves to get a penetration function for a particular device.

Since the range of the EPA penetration functions did not extend out to 100 μm as required for calculating the TSP emissions, it was necessary to extrapolate the EPA functions. For device codes 1, 2, 3, 10, 11, 12, 16, 17, and 18 the EPA equations were simply extrapolated to 100 μm using the functional form given for large particles. The EPA equations for device codes 7, 8, and 9 were quadratic up to 15 μm and had a minimum there. Extrapolation of the function beyond 15 μm would have resulted in a penetration that increased with particle size beyond 15 μm, a behavior considered unlikely. For these three device codes, the minimum penetration at 15 μ was assumed to apply through the 15-100 μm range.

*Although shown as a separate data file in Fig. 1.2A, the penetration functions were actually included within the CRAIG programs.

Table 2.4 EPA Penetration Functions

Control Device		Size Range,	
Code[a]	Type	D(μm)	Functional Penetration, P
1	High Efficiency Scrubber[b]	$0.1 \leq D < 0.2$	$P = 1.2 \exp-(2.31 \log D + 0.69897)^2$
		$0.2 \leq D \leq 15$	$P = 0.53 \exp-(\log D + 0.69897)^2$
2	Medium Efficiency Scrubber[c]	$0.1 \leq D < 0.2$	$P = \frac{(D - 0.2)^2}{-0.0208} + 0.68$
		$0.2 \leq D \leq 15$	$P = 0.68 \exp-(\log D - 0.69897)^{1.4}$
3	Low Efficiency Scrubber[d]	$0.1 \leq D < 0.2$	$P = \exp-(1.61 \log D + 0.69897)^2$
		$0.2 \leq D \leq 15$	$P = 0.8 \exp-(\log D + 0.69897)^2$
7,8,9	Mechanical Collectors	$0.1 \leq D < 1.42$	$P = 1.0$
		$1.42 \leq D < 5.0$	$P = \exp-4(\log D - \log 1.42)^2$
		$5.0 \leq D \leq 15.0$	$P = \frac{(D - 15)^2}{555} + 0.12$
10	High Efficiency ESP[e]	$0.1 \leq D < 0.28$	$P = 0.36 \exp-3 (\log D + 0.552842)^2$
		$0.28 \leq D \leq 15$	$P = 0.36 \exp-1.7 (\log D + 0.552842)^2$
11,12	Low and Medium Efficiency ESP's[f]	$0.1 \leq D \leq 15$	$P = 0.7 \exp-1.4 (\log D + 0.552842)^2$
16,17,18	Fabric Filters	$0.1 \leq D \leq 0.15$	$P = 0.1$
		$0.15 \leq D < 1.0$	$P = -0.12137 \log D + 0.05$
		$1.0 \leq D < 1.0$	$P = -0.05 \log D + 0.05$
		$10 \leq D \leq 15$	$P = 0.0001$

[a]NEDS device code.

[b]40" pressure drop.

[c]20" pressure drop.

[d]10" pressure drop.

[e]99% design efficiency.

[f]95% design efficiency.

There were several device codes not covered by the EPA curves. Table 2.5 lists the additional penetration functions developed for this work. Gravity collectors collect only particles larger than about 40-50 μm.[9,10] The formulas provide a step function at 40 μm with no collection below 40 μm and the inventoried collection efficiency above 40 μm. The renormalization procedure would provide the inventoried overall TSP control efficiency and still allow full penetration by PM10 (< 10 μm). The penetration functions for mist eliminators, device codes 14 and 15, were developed by approximating typical efficiency curves in Ref. 9. The low velocity mist eliminator was assumed to correspond to a pressure drop of zero and the equation for the high velocity mist eliminator was taken to be a reasonable average of the curves presented for pressure drops greater than zero. For process changes, device code 46, no real basis exists for assigning a functional form and the inventoried efficiency was used for all sizes of particles. For incorrect codes or missing codes, the absence of controls was assumed.

The necessity for the introduction of the renormalization factor ω in Eq. 2.2.17 should be clear at this point. Use of the equations in Tables 2.4 and 2.5 provides a single overall collection efficiency for a particular input distribution of particle sizes. This efficiency could and did differ substantially from the inventoried TSP efficiency. Simply applying

Table 2.5 Additional Penetration Functions

Control Devices		Size Range	Fractional
Code	Type	D (μm)	Penetration, P
4,5,6	Gravity Collectors	$0.1 \leq D < 40$	$P = 1.0$
		$40 \leq D \leq 0.1$	$P = 1 - \eta_{INV}/100$
14	High Velocity Mist Eliminator	$0.1 \leq D < 10$	$P = 1 - 0.5\ (\log D + 1)$
		$10 \leq D \leq 100$	$P = 0$
15	Low Velocity Mist Eliminator	$0.1 \leq D \leq 4.0$	$P = 1.0$
		$4.0 < D < 20.0$	$P = 1.68908 - 1.1445 \log D$
		$20.0 \leq D \leq 100$	$P = 0.20$
46	Process Change	$0.1 \leq D \leq 100$	$P = 1 - \eta_{INV}/100$
≤ 0	None or bad code	$0.1 \leq D \leq 100$	$P = 1.0$

the curves to calculate PM10 emissions without regard to this possibility can lead to situations in which PM10 emissions exceed TSP emissions for a particular source. Recognition that such situations could and did occur led to the use of renormalization as described above.

2.2.2 Area Source Emission Inventory

TSP Inventory. A different approach to the development of area source emissions was used here than was used in the earlier model by EEA. The procedure employed here ensured that the area source emissions used to project air quality were the same as those available for control during strategy development. The available data consisted of total area source emissions by county gathered from EPA's NEDS files.[2] There was no breakdown by the type of area source. In counties with several analysis areas, the only available estimate of area source emissions was that for the county as a whole.

Factors for converting TSP emissions to PM10 emissions were available for paved and unpaved municipal roads. In addition, paved municipal roads were assumed to be controllable during strategy development. Thus, a procedure for estimating the emissions from both types of municipal roads was required. In the EEA model, two different methods were used to estimate emissions from paved municipal roads. In consultation with EPA, it was decided that these methods of estimating municipal road emissions were probably preferable to using the NEDS estimates even if the latter had been available directly in the inventory. One of these methods was chosen for this work and used to calculate both the base-year emissions and the potentially controllable emissions thus ensuring consistency in the magnitude of the emissions from paved municipal roads throughout the anlaysis system.* The overall procedure was therefore one requiring the estimation of paved and unpaved municipal road emissions based on the county-wide total and substitution of a new estimate for the emissions from paved roads. The procedure employed is described below.

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*The second method of calculation as well as a method for calculating emissions from unpaved municipal roads were not used here simply because they were embedded in the computer codes in such a fashion as to require a significant restructuring of the system to make use of them.

Let $Q_i(j)$ = emissions of pollutant j from area source category i

where:

i = A for total emissions from all area sources,
P for emissions from paved municipal roads,
U for emissions from unpaved municipal roads,
O for emissions from all area sources other than municipal roads,

and

j = TSP for total suspended particulates and
PM10 for particulate matter less than 10 μm.

Then

$$Q_A(TSP) = Q_P(TSP) + Q_U(TSP) + Q_O(TSP). \quad (2.2.27)$$

The emissions in each category i could be estimated from the total emissions if the fraction of total area source emissions in each category, f_i, were known. These fractions were estimated from the current NEDS area source inventory by the RATIOS program (see Fig. 1.2A):

$$f_i = \frac{\text{Current NEDS emissions for area source category i}}{\text{Current NEDS total area source emissions}}. \quad (2.2.28)$$

It follows that

$$\sum_{U,P,O} f_i = 1 \text{ and } f_i \leq 1. \quad (2.2.29)$$

Equation 2.2.27 can now be rewritten as

$$Q'_A(TSP) = Q_P(TSP) + f_U Q_A(TSP) + f_O Q_A(TSP) \quad (2.2.30)$$

where the prime indicates that the estimate of total area emissions in Eq. 2.2.30 may be different from that in the EEA inventory and the assumption has been made that disaggregating the base year inventory using f_U and f_O calculated from the current NEDS inventory produces an error of an acceptable magnitude. In the earlier model, emissions from paved municipal roads were calculated from urban and rural vehicle-miles-traveled (VMT_u and VMT_r, respectively). Values for VMT were available for each county in the EEA data sets (file 3.5 in Fig. 1.2A) and a new estimate of emissions from paved municipal roads $\hat{Q}_P$ was obtained from

$$\hat{Q}_P(TSP) = 0.00488 \times VMT_u + 0.000905 \times VMT_r \quad (2.2.31)$$

as discussed in Ref. 2 and where the numerical coefficients have been chosen to appropriately adjust the units. The value of $\hat{Q}_P$ was substituted for Q_P in Eq. 2.2.30 to obtain a final adjusted estimate for base year emissions from area sources $\hat{Q}_A$ given by

$$\hat{Q}_A(\text{TSP}) = \hat{Q}_P(\text{TSP}) + f_U Q_A(\text{TSP}) + f_O Q_A(\text{TSP})$$

$$= \hat{Q}_P(\text{TSP}) + \hat{Q}_U(\text{TSP}) + \hat{Q}_O(\text{TSP}). \qquad (2.2.32)$$

The estimates of area source TSP emissions given by Eq. 2.2.32 and the estimates for each of the three subcategories were used whenever area sources were treated by the analysis system. These calculations were carried out in the GROWTH program. It was also computationally convenient to redo the calculations in various other programs but these details have been omitted from Fig. 1.2 as being unnecessary to an understanding of the basic calculations.

PM10 Inventory. Once TSP emissions were available for the three subcategories, the estimation of PM10 emissions was straightforward although hardly precise. Using emission factors and size data for reentrained road dust and assuming a log-normal distribution of particle sizes, ratios of total PM10 to total TSP emissions, R_i, were calculated for paved and unpaved roads. The values obtained were

$$R_U = 0.15 \text{ and } R_P = 0.69.$$

For all other area source categories, a value $R_O = 0.40$ was used. A single value for R_O is probably not realistic, since the source mix in the category varies between counties and the particle size distributions are likely to vary with source category. The chosen value was consistent with some recent analysis presented in Ref. 11. These ratios were applied term-by-term to Eq. 2.2.32 in the GROWTH program to estimate base-year county-wide emissions of PM10 from area sources:

$$\hat{Q}_A(\text{PM10}) = 0.69 \times \hat{Q}_P(\text{TSP}) + 0.15 \times f_U Q_A(\text{TSP}) + 0.40\, f_O Q_A(\text{TSP})$$

$$= \hat{Q}_P(\text{PM10}) + \hat{Q}_U(\text{PM10}) + \hat{Q}_O(\text{PM10}). \qquad (2.2.33)$$

2.3 CONTROL OPTIONS AND COSTS

TSP Data. This section discusses the data represented by box 13 in Fig. 1.1 and file 7.2 in Fig. 1.2B. For TSP, the data originally developed by EEA[2,3] was used with no changes. It was assumed for this work that the same control devices would be used for PM10 as were used for TSP, that is, that the size, capital costs, and O&M costs would not depend upon the pollutant being controlled. This work extended the EEA data to include estimates of PM10 control efficiencies.

The information developed for TSP contained control options and the associated costs for SCC's contributing significantly to national TSP emissions. In addition to these stack sources, information was available for the control of nontraditional fugitive dust and reentrained road dust from municipal roads. For stack sources, costs depend upon air flow; larger air flows require larger and more expensive control devices. Since air flow was frequently unavailable or unreliable in the emissions inventory, surrogate variables were used in estimating costs.

Cost equations were developed for each SCC/option pair by regression from literature estimates to give equations of the form:

$$Y = a(k_1X_1)^b(k_2X_2) \qquad (2.3.1)$$

where

Y = cost in dollars per year per unit source size,

X_1, X_2 = variables depending on source type, size, and control device,

k_1, k_2 = constants for transforming units, and

a, b = regression constants.[2,3]

In many cases, the factor in X_2 was not used. For process sources, the capital costs generally depended only on the maximum operating rate and O&M costs depended only on the average operating rate. This procedure gave a capital cost depending on the maximum flow and O&M costs based on the average conditions of operation. For boilers, heat input, maximum operating rate, or megawatts of electrical capacity were used to estimate capital costs. O&M costs for boilers depended upon heat inputs or megawatts capacity and operating rate. Costs for storage piles depended upon the tons of material handled and road miles were used as cost-estimating variable for all roads. The independent variables (X_1, X_2) were available in the emissions inventory

for stack and nontraditional fugitive sources. The estimation of road miles for municipal paved roads is discussed in Sec. 4.2.

Up to three options were available for a particular SCC. Since the equipment was to be retrofitted on existing installations, an estimated 50% retrofit penalty was added to all capital costs. In fact, wide variation exists in the magnitude of the retrofit penalty, but it was not possible to model that variation within the scope of this project.

Extension to PM10. Estimates of the control efficiencies for PM10 were made using the procedures already described in Sec. 2.2.1 and implemented by one of the versions of CRAIG, shown as CRAIG-II in Fig. 1.2B. Given the SCC of the process and the control device associated with the option of interest, the normalized TSP distribution S(D) and the penetration function P(D) could be found. Then, using Eq. 2.2.11 C(100) could be found and the ω corresponding to the assumed TSP control efficiency of the option, η_{TSP}, could be calculated from Eq. 2.2.19. The calculated PM10 efficiency of the option must, of course, be renormalized as discussed previously. This efficiency $H_R(10)$ is given by

$$H_R(10) = \frac{Q_c^R(10) - Q_u^T(10)}{Q_u^T(10)}$$

$$= 1 - \frac{C_R(10) \times TSP_{unc}^A}{U(D) \times TSP_{unc}^A}$$

$$= 1 - \frac{C_R(10)}{U(10)}. \qquad (2.3.2)$$

This equation is analogous to Eq. 2.2.18 for TSP, as in fact, it must be, since the derivation is really independent of particle size.

For nontraditional fugitives and municipal roads, the control efficiency for PM10 was equal to the control efficiency for TSP. This happened because there was no information on the size-dependent control efficiencies of the options for these sources. Thus, the default assigning equal efficiencies for TSP and PM10 was used.

No defaults were assigned for source categories (SCC's) not on the original list of options. Any source whose SCC was not on the list was not a

candidate for control during development of the control strategy. This procedure led to cases where some subprocesses within a particular process were candidates but others were not. For example, the EEA file contained an option for the control of leaks from coke oven doors but no options for the control of emissions from charging, pushing, or quenching. It should be recalled that the SCC's with control options accounted for a significant fraction of national TSP emissions.

2.4 GROWTH AND RETIREMENT RATES

This section outlines the development of the data associated with box 2 in Fig. 1.1 and files 3.6 and 3.8 in Fig. 1.2A. Additional detail is provided in Ref. 2. The estimates of growth and retirement rates made by EEA were used without alteration for this work.

A reasonable estimate of future emissions and air quality must account for the fact that major new sources and modifications will usually be subject to more stringent control requirements than existing sources. State air pollution regulations are frequently drafted to require this additional control or it is required by New Source Performance Standards (NSPS), Prevention of Significant Deterioration (PSD), or new source review procedures for nonattainment areas. These new and modified sources result either from construction to increase capacity (growth) or from construction to replace old sources being retired. To estimate the emissions and air quality impacts of new sources subject to more stringent control requirements, growth and retirement rates were needed.

Based on projections of value added by the Bureau of Economic Analysis (BEA) of the U.S. Department of Commerce for the period 1975-1995, EEA estimated compound growth rates for each state at the two-digit SIC level. BEA estimates of population growth were used to estimate compound population growth rates at the state level. These latter supplied defaults when SIC-specific growth rates were not available and were used in the projection of growth in area source emissions.

EEA also developed estimates of compound retirement rates. These were national average values at the two-digit SIC level developed from retirement data provided by Data Resources, Inc. (DRI). At five year intervals, the DRI data gave the cumulative fraction of total annual retirement accounted for by plant investment initiated in each preceeding five-year period.

3 PROJECTING FUTURE NONATTAINMENT

Prior to the development of a control strategy an estimate of future air quality is needed for comparison with the standards to determine whether any additional controls are needed and, if so, the air quality improvement required from such controls. The MARGIN program in Fig. 1.2A carries out both the projection and comparison functions. This process corresponds to boxes 4,6,7,9, and 10 in Fig. 1.1 and requires that future air quality be projected based on the base-year air quality, the base-year emission inventories, and the estimates of growth and retirement rates. One procedure for making these estimates begins with the estimation of future county emissions and uses the estimate for a particular county to adjust the base-year air quality for each analysis area within that county for comparison with the standards and the selection of a binding year and binding standard. Although inconsistent with the use of weighted coupling coefficients used in the development of the control strategy, this procedure was deeply embedded in the processing sequence of the EEA system[1,2] and could not be changed within the time available for this work.* Despite the retention of this inconsistency, significant changes were made in the procedure used to project future emissions in the earlier model, necessitating a fairly complete description of this work's procedure in Sec. 3.1. Section 3.2 describes the estimation of future air quality and the choice of the binding year and standard.

3.1 PROJECTING FUTURE EMISSIONS

This section describes the procedures represented by box 4 in Fig. 1.1, as well as some of the input parameters included in box 7. Different procedures were used for point sources (Sec. 3.1.1) and for area sources (Sec. 3.1.2). Tables A.1, A.2, and A.3 in Appendix A present projections of PM10 emissions at the National level by source category, at the Regional level, and at the Sectional level, respectively.

3.1.1 Projection of Point Source Emissions

As already noted, new or replacement point sources are frequently subject to more stringent control requirements than old or unmodified point sources. In this section, a discussion of the estimation of the efficiencies

*The nature and consequences of this inconsistency are discussed more fully in Sec. 4.1 dealing with source-specific coupling coefficients.

of such new source (NS) controls is postponed until after the projection methodology is described.

Methodology

Emissions projections, including estimates of the emissions from growth and replacement sources, were made on a source-by-source basis. This procedure is unrealistic in the sense that operationally a particular base-year source is replaced by an unreplaced fraction, a replaced fraction, and a growth fraction. Such an approach does not correspond to reality where sources are discrete units that are either entirely present or entirely absent from the inventory assuming that the capacity utilization factor for an old source remains unchanged. From the county-level perspective, however, the approach is more reasonable because applying average behavior to each source individually should provide a reasonable estimate of overall emissions if the number of sources involved is sufficiently large and if their ages are properly distributed over the lifetime range of the appropriate source type. Of course, in some counties, these conditions might not be satified. Other approaches in which attempts are made to account for the age of individual sources run into difficulties in determining source-specific ages which are not available in standard emission inventories. A method of assigning estimated ages to individual sources must then be chosen and is subject to the same vagueries, and, in fact, would probably use the same data, as are associated with the application of national average retirement rates to individual sources. The approach used here was relatively easy to implement, because projections on a source-by-source basis were already built into the earlier EEA model. To have implemented a procedure based on specific ages for each source would have required a significant change in the basic structure of the earlier system without introducing any significant improvement in the accuracy of the results.

The basic problem is then one of estimating the future emissions of a point source subject to both growth and retirement. We define*

g = growth rate (fraction per year),

*In the interests of brevity, the notation used in this section is simpler than that used in Sec. 2. However, no confusion should result, because although the projections used the information from the inventory, they were conceptually as well as computationally distinct from the process of inventory development.

r = replacement rate (fraction per year),

Q_o^u = uncontrolled emission rate in base year,

Q^u = uncontrolled emission rate in projection year, and

Δt = years involved in projection

= (projection year) - (base year).

It is also convenient to define

$$G = (1 + g)^{\Delta t} - 1 = \text{incremental fractional growth } \Delta t \text{ years after base year} \qquad (3.1.1)$$

and

$$R = 1 - (1 - r)^{\Delta t} = \text{fractional retirement } \Delta t \text{ years after base year, } 0 \leq R < 1. \qquad (3.1.2)$$

The growth rate g is usually positive but may be zero or negative while the replacement rate r is always positive or zero. Estimates of g and r for stack sources came from the available basic data (box 2 in Fig. 1.1 and file 3.6 in Fig. 1.2A). A replacement rate of r = 0 was applied to nontraditional fugitive sources. Operationally, emissions from these sources were inventoried as point sources and were projected as if they were point sources. Since the concept of retirement is inappropriate for plant roads and storage piles, setting r = 0 for these sources removes the possibility of making an inappropriate emission projection. Q_o^u comes from the point source inventory (box 1) for the appropriate pollutant and 1978 is taken as the base year.

Figure 3.1 shows how uncontrolled emissions from a single source are projected. Even though the procedure to be discussed was applied to each source individually, the concepts involved are more easily understood by considering a large number of individual sources as is done in the following discussion. Three distinct cases must be considered corresponding to the relative sizes of g and r or G and R. Although not actually implemented in exactly this way, the projection of future emissions can be imagined as taking place in two steps. First, uncontrolled emissions are projected in three different categories:

Q_1^u = uncontrolled emissions from the base-year unretired fraction of the sources Δt years after the base year,

Q_2^u = uncontrolled emissions from the fraction of the original source replaced by new sources, and

Q_3^u = uncontrolled emissions from the new growth sources.

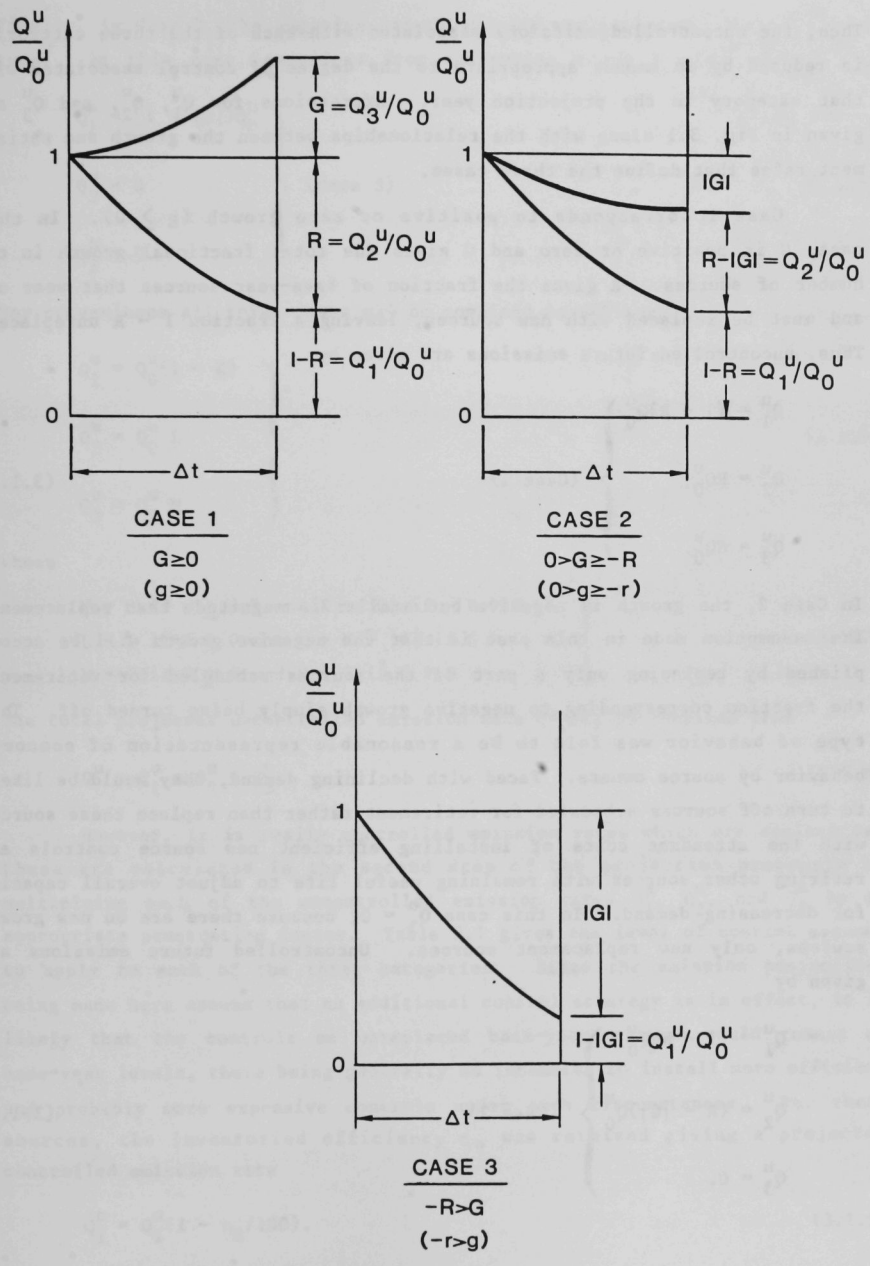

Fig. 3.1 Projecting Future Emissions

Then, the uncontrolled emissions associated with each of the three categories is reduced by an amount appropriate to the degree of control associated with that category in the projection year. Expressions for Q_1^u, Q_2^u, and Q_3^u are given in Fig. 3.1 along with the relationships between the growth and retirement rates that define the three cases.

Case 1 corresponds to positive or zero growth ($g \geq 0$). In this case, G is positive or zero and G gives the total fractional growth in the number of sources. R gives the fraction of base-year sources that wear out and must be replaced with new sources, leaving a fraction 1 - R unreplaced. Thus, uncontrolled future emissions are given by

$$\left.\begin{aligned} Q_1^u &= (1 - R)Q_0^u \\ Q_2^u &= RQ_0^u \\ Q_3^u &= GQ_0^u. \end{aligned}\right\} \text{ (Case 1)} \qquad (3.1.3)$$

In Case 2, the growth is negative but smaller in magnitude than replacement. The assumption made in this case is that the negative growth will be accomplished by replacing only a part of the sources scheduled for retirement, the fraction corresponding to negative growth simply being turned off. This type of behavior was felt to be a reasonable representation of economic behavior by source owners. Faced with declining demand, they would be likely to turn off sources scheduled for retirement rather than replace these sources with the attendant costs of installing efficient new source controls and retiring other sources with remaining useful life to adjust overall capacity for decreasing demand. In this case $Q_3^u = 0$, because there are no new growth sources, only new replacement sources. Uncontrolled future emissions are given by

$$\left.\begin{aligned} Q_1^u &= (1 - R)Q_0^u \\ Q_2^u &= (R - |G|)Q_0^u \\ Q_3^u &= 0. \end{aligned}\right\} \text{ (Case 2)} \qquad (3.1.4)$$

Finally, in Case 3, the negative growth exceeds the retirement rate in magnitude. In this case, emissions from categories 2 and 3 would be zero and

$$\left.\begin{aligned} Q_1^u &= (1 - |G|)Q_0^u \\ Q_2^u &= 0 \\ Q_3^u &= 0. \end{aligned}\right\} \text{ (Case 3)} \qquad (3.1.5)$$

For convenience all three cases may be combined as follows:

$$\left.\begin{aligned} Q_1^u &= Q_0^u(1 - K) \\ Q_2^u &= Q_0^u\, L \\ Q_3^u &= Q_0^u\, M. \end{aligned}\right\} \qquad (3.1.6)$$

where

$$\left.\begin{aligned} &K = R \text{ if } G \geq -R \text{ and } K = |G| \text{ if } -R > G, \\ &L = K \text{ if } G \geq 0 \text{ and } L = K - |G| \text{ if } 0 > G, \text{ and} \\ &M = G \text{ if } G \geq 0 \text{ and } M = 0 \text{ if } 0 > G \end{aligned}\right\} \qquad (3.1.7)$$

The total projected uncontrolled emission rate Q^u may be obtained from

$$Q^u = Q_1^u + Q_2^u + Q_3^u. \qquad (3.1.8)$$

However, it is really controlled emission rates which are desired and these are calculated in the second step of the projection procedure by multiplying each of the uncontrolled emission rates Q_1^u, Q_2^u, and Q_3^u by an appropriate penetration factor. Table 3.1 gives the level of control assumed to apply to each of the three categories. Since the emission projections being made here assume that no additional control strategy is in effect, it is likely that the controls on unreplaced base-year sources would remain at base-year levels, there being generally no incentive to install more efficient and probably more expensive controls under such circumstances. For these sources, the inventoried efficiency η_o was retained giving a projected controlled emission rate

$$Q_1^c = Q_1^u(1 - \eta_0/100). \qquad (3.1.9)$$

Table 3.1 Emission Projections - Control Assumptions

Projected Uncontrolled Emission Rate		Fraction of Category	Assumed Level of Control[a]	Projected Controlled Emission Rate[b]
Category	Description			
Q_1^u	Base-Year Sources Not Replaced	All	Base-Year	$Q_1^u(1 - \eta_o/100)$
Q_2^u	New Replacement Sources	b	Base-Year	$bQ_2^u(1 - \eta_o/100)$
		1 - b	NS	$(1 - b)Q_2^u(1 - \eta_n/100)$
Q_3^u	New Growth Sources	a	Base-Year	$aQ_3^u(1 - \eta_o/100)$
		1 - a	NS	$(1 - a)Q_3^u(1 - \eta_n/100)$

[a] NS: New source level controls.

[b] η_o: Base-Year control efficiency.
η_n: NS control efficiency.

Implicit in this approach are two further assumptions. First, even if current controls are more efficient than required by current regulations, these controls will not be replaced by less efficient controls. Second, the inventoried controls represent compliance emission levels, that is, a particular source will continue to apply the current level of control in the absence of additional control programs. In this context it should be noted that current TSP standards were one of the alternative standards considered. At least some fraction and probably quite a large fraction of the inventoried particulate controls were installed in an attempt to attain these standards. Thus, any controls applied during strategy development for the current TSP standard represent incremental controls beyond those already inventoried and installed in earlier attempts to achieve the same standards.

It is frequently assumed that all new sources, both replacement and growth, would need to meet new source (NS) control levels. However, at least for replacement sources, the situation is not entirely clear. Included in replacement may be modifications that may not always be required to achieve NS control levels. In addition, consultation with EPA indicated that replacement sources might not always be reviewed as thoroughly or as completely as new sources and that frequently replacement sources, as defined in the development of the replacement rates, would not fall under the definition of

"new sources" subject to NS level controls. To account for this, a fraction b was defined such that

b = the fraction of replacement sources coming on at current control levels.

Then

(1 - b) = the fraction of replacement sources coming on at NS levels.

A similar fraction was also defined for new growth sources:

a = the fraction of growth sources coming on at current control levels.

The factors a and b can be changed between various runs through the analysis system and are included among the input parameters (box 7 in Fig. 1.1 and file 4.3 in Fig. 1.2A). The base analysis scenarios were run with a = 0 and b = 0.5, that is, the data used for the RIA and for other analyses assumed that all growth sources but only one-half of the replacement sources would be required to apply NS level controls. A fraction b of replacement sources and a fraction a of growth sources would thus be controlled to current control levels (η_o) while fractions (1 - b) and (1 - a) would be controlled to NS levels (η_n). The future emissions for categories 2 and 3, Q_2^c and Q_3^c are then given by

$$Q_2^c = bQ_2^u(1 - \eta_o/100) + (1 - b)Q_2^u(1 - \eta_n/100) \tag{3.1.10}$$

and

$$Q_3^c = aQ_3^u(1 - \eta_o/100) + (1 - a)Q_3^u(1 - \eta_n/100). \tag{3.1.11}$$

The total controlled future emissions Δt years after the base year, $Q^c(\Delta t)$, is given by

$$\begin{aligned} Q^c(\Delta t) &= Q_1^c + Q_2^c + Q_3^c \\ &= Q_0^u[(1 - K + bL + aM)(1 - \eta_o/100) \\ &\quad + \{(1 - b)L + (1 - a)M\}(1 - \eta_n/100)] \\ &= Q_0^c\left[(1 - K + bL + aM) + \{(1 - b)L \right. \\ &\quad \left. + (1 - a)M\}\left(\frac{1 - \eta_n/100}{1 - \eta_o/100}\right)\right] \end{aligned} \tag{3.1.12}$$

where the time dependence is included in K, L, and M.

There is nothing in the derivation of Eq. 3.1.12 that depends upon the pollutant of interest except that Q_0^c, η_o, and η_n must be for the same pollutant. Equation 3.1.12 was, however, only used for projecting TSP emissions. Because of the manner in which estimates of NS control efficiencies were made, a somewhat different but equivalent approach was followed for PM10. For PM10, Eq. 3.1.12 becomes

$$Q^c(\text{PM10}) = Q_0^c(\text{PM10})(1 - K + bL + aM) + Q_0^c(\text{PM10}) \left\{(1 - b)L + (1 - a)M\right\} \left(\frac{1 - \eta_n'/100}{1 - \eta_o'/100}\right) \qquad (3.1.13)$$

where primes have been used to indicate PM10 efficiencies. We define a quantity F_n giving the ratio of controlled PM10 emissions to controlled TSP emissions at NS levels, that is,

$$F_n = \frac{Q_n^c(\text{PM10})}{Q_n^c(\text{TSP})} = \frac{Q_0^u(\text{PM10})(1 - \eta_n'/100)}{Q_n^c(\text{TSP})} \qquad (3.1.14)$$

and rewrite the second term of Eq. 3.1.13:

$$\begin{aligned}
&Q_0^c(\text{PM10}) \left\{(1 - b)L + (1 - a)M\right\} \left(\frac{1 - \eta_n'/100}{1 - \eta_o'/100}\right) \\
&= Q_0^c(\text{PM10}) \left\{(1 - b)L + (1 - a)M\right\} \left(\frac{1 - \eta_n'/100}{1 - \eta_o'/100}\right) \left(\frac{1 - \eta_n/100}{1 - \eta_o/100}\right) \left(\frac{1 - \eta_o/100}{1 - \eta_n/100}\right) \\
&= Q_0^u(\text{PM10}) \left\{(1 - b)L + (1 - a)M\right\} (1 - \eta_n'/100) \left(\frac{1 - \eta_n/100}{1 - \eta_o/100}\right) \left(\frac{1 - \eta_o/100}{1 - \eta_n/100}\right) \\
&= Q_n^c(\text{PM10}) \left\{(1 - b)L + (1 - a)M\right\} \left(\frac{1 - \eta_n/100}{1 - \eta_o/100}\right) \left(\frac{1 - \eta_o/100}{1 - \eta_n/100}\right) \\
&= F_n Q_n^c(\text{TSP}) \left\{(1 - b)L + (1 - a)M\right\} \left(\frac{1 - \eta_n/100}{1 - \eta_o/100}\right) \left(\frac{1 - \eta_o/100}{1 - \eta_n/100}\right).
\end{aligned}$$

Noting that

$$Q_n^c(\text{TSP}) \left(\frac{1 - \eta_o/100}{1 - \eta_n/100}\right) = Q_0^u(\text{TSP})(1 - \eta_o/100) = Q_0^c(\text{TSP}),$$

Eq. 3.1.13 for PM10 may then be rewritten as

$$Q^c(\text{PM10}) = Q_0^c(\text{PM10})(1 - K + bL + aM)$$

$$+ F_n Q_0^c(\text{TSP}) \left[(1 - b)L + (1 - a)M\right] \left(\frac{1 - \eta_n/100}{1 - \eta_o/100}\right). \qquad (3.1.15)$$

The quantities Q_0^c (TSP) and Q_0^c (PM10) were available in the inventory and the F_n which depend on the specific process (SCC), control device, and efficiency being considered, were calculated as described in the following subsection. The TSP base-year control efficiency η_o was also taken from the inventory and the values used for the TSP efficiency corresponding to NS control levels, η_n, are also described below.

NS Control Levels

As already noted, requiring efficient NS control levels on some growth and replacement sources was an attempt to simulate the effect of several programs, primarily NSPS, PSD, and new source review in nonattainment areas. These programs frequently deal only with large or major sources, for example, boilers with capacities exceeding 250 MMBtu/hr or sources emitting more than 100 tons/yr. On the other hand, state regulations frequently require some small new sources to achieve emission levels below those required of existing sources. No attempt was made in the earlier model to apply NS controls exclusively to large new sources; they were assumed to be required on all growth and replacement sources. This problem might be alleviated somewhat by adjusting the factors a and b so that not all growth and replacement sources would be controlled to NS levels. It was not possible to investigate this possibility in detail in a timely fashion.

New Source Control Levels for TSP. Estimates of NS control levels for TSP were included in the EEA model.* Upon review of various NSPS's and BACT clearing-house information, two generic NS control efficiencies were defined:[2]

*In the EEA documentation, NS controls are referred to as BACT. The name has been changed here to avoid confusion, because BACT is really only appropriate to the PSD program.

$$\left.\begin{aligned}\hat{\eta}_n \text{ (SIC 33)} &= 98\% \text{ and} \\ \hat{\eta}_n \text{ (All other SICs)} &= 99\%.\end{aligned}\right\} \quad (3.1.16)$$

Use of these numbers can cause anomalous behavior. Some sources in the base-year inventory had inventoried efficiencies greater than 99%. For these sources, the process of replacement at NS levels would lead to emissions increasing over time even in the absence of growth as efficient current controls were replaced with less efficient NS controls. It seemed more realistic to assume that the use of less efficient controls than were currently in place would be unlikely under programs whose purpose was the reduction of emissions through the stringent control of new sources. Therefore, the definition of NS controls (η_n) adopted for this work was extended to be

$$\eta_n(\text{TSP}) = \text{MAX}\,[\hat{\eta}_n,\ \eta_{INV}(\text{TSP})]. \quad (3.1.17)$$

With this modification, replacement at NS levels could not lead to emissions increasing over time.

Two additional problems with the definition of NS levels of control were left unresolved in this work. First, there is another set of efficiencies (η_s) associated with the imposition of the control strategy for any particular source. It can occur that $\eta_n < \eta_s$. In such cases, anomalies similar to those just discussed can arise when emissions are projected beyond the year in which the control strategy was imposed. A fuller discussion of this problem must await the explanation of the development of the control strategy and is included in Sec. 4.3. Second, there is good reason for expecting that controls more efficient that those required by NSPS or BACT under PSD are available. This is the principal consideration, for example, behind the requirement for LAER in nonattainment areas. Insofar as a single point estimate of η_n can be expected to simulate all three programs (NSPS, PSD, and nonattainment), it may not be reasonable to choose the most efficient available estimate for η_n, particularly when that most efficient estimate is chosen from among values to be applied in nonattainment areas. Procedures for avoiding the problems just alluded to were precluded by the need to completely restructure the earlier model in order to implement them.

New Source Control Levels for PM10. Due to the differences in the particle size distributions for different SCC's a TSP efficiency of, say, 99% could correspond to a range of PM10 efficiencies. Because no control device was specified with the generic estimates of η_n in Eq. 3.1.16, the methods of Sec. 2.2 could not be applied to the estimation of NS efficiencies for PM10. Instead estimates were made for the factors F_n (see Eq. 3.1.14) for each SCC and for various ranges of inventoried TSP control efficiencies. These calculations were carried out by CRAIG-I and the results correspond to file 3.1 in Fig. 1.2A. Ranges were chosen instead of single point estimates in an attempt to average over the various types of control devices used on a particular SCC. Given the definition of η_n (TSP) in Eq. 3.1.17 and the values for $\hat{\eta}_n$ in Eq. 3.1.16, only inventoried TSP efficiencies near or greater than 98% needed to be considered. The ranges actually considered were:

$$99.7\% \leq \eta_{INV}(TSP)$$
$$99.4\% \leq \eta_{INV}(TSP) < 99.7\%$$
$$99.1\% \leq \eta_{INV}(TSP) < 99.4\%$$
$$98.8\% \leq \eta_{INV}(TSP) < 99.1\%$$
$$98.5\% \leq \eta_{INV}(TSP) < 98.8\%$$
$$97.5\% \leq \eta_{INV}(TSP) < 98.5\%.$$

Given the inaccuracies associated with the use of only two single values for the generic estimates of NS levels in the first place, these ranges were considered sufficiently narrow to provide a reasonable degree of accuracy.

For each SCC, the inventoried sources with $\eta_{INV}(TSP)$ lying in a particular range of efficiencies, j, were identified. For each such source, i, the ratio

$$f_i(SCC,j) = \frac{Q_i^R(10)}{Q_i^R(100)}, \tag{3.1.18}$$

the ratio of the renormalized, controlled emission rates for PM10 and TSP was calculated using the methods of Sec. 2.2. Finally, F_n was calculated as the average of all appropriate f_i's:

$$F_n(SCC,j) = \frac{1}{N} \sum_{i=1}^{N} f_i(SCC,j) \tag{3.1.19}$$

assuming that N sources had been identified. Of course, there were combinations of efficiency range and SCC for which no sources were identified. For these cases, defaults based on the default particle size distributions for combustion and noncombustion sources were used.

In applying Eq. 3.1.12 for projecting TSP emissions for a particular source, the value of η_n defined by Eq. 3.1.17 could be used directly. To find the appropriate F_n for projecting PM10 emissions, the range j_n corresponding to this value of η_n was determined and the value of F_n (SCC, j_n) was used in the calculation.

3.1.2 Projection of Area Source Emissions

General. The approach taken with area sources is different from that taken with point sources. Growth rates were not available for individual categories of area sources. In the earlier model, all area source emissions were assumed to grow at the same rate as population.[2] Population growth rates were available for each state. However, emissions from some area source categories like wind erosion and agricultural tilling might grow at a rate unrelated to population or might even decrease as population increases. In discussion with EPA it was decided that population growth was a reasonable projection parameter for emissions from paved municipal roads, more roads and roadway traffic generally being needed as population increases. Lacking any other reasonable growth parameters, population growth was retained as the projection parameter for all other area source categories including unpaved municipal roads. It might be argued that all municipal roads would grow at the same rate as population. While this may be true, expanding populations generally tend to lead to the paving of formerly unpaved roads by demanding and supporting upgraded services. Based on such considerations, provision was made to permit only some input fraction of the other area sources to grow, that is, to reduce the effective growth rate of the other area sources to below the population growth rate.

Evidence is available to indicate that reentrained road dust from paved roads has only a limited effective range. An attempt was made in this work to incorporate this effect by defining an effective fraction for paved municipal

roads. The inventoried emissions from paved municipal roads were reduced in the base year prior to projection to account for the fact that only a limited fraction of them would affect the design value monitor. This approach was taken in the earlier model during strategy development where only a fraction of the paved roads in an area were assumed to be effective in reducing concentrations at the receptor of interest.[2] In this work, the effective fraction concept has been extended to the base year and to the projection of future air quality to ensure consistency between emissions projections and strategy development.

It should be noted that an entirely consistent approach to road emissions would have required the reduction of emissions from the paved plant roads included in the nontraditional fugitive emissions by the same effective fraction as was used for municipal roads. There appears to be no reason for assuming that the plant roads in an area have relatively more impact on the receptor of interest than the municipal roads unless additional information is available to indicate that a larger fraction of the plant roads are within the effective range from the receptor than is the case for the municipal roads. This type of problem is inherent in using rollback with no spatial resolution and attempting to simulate within a system using it features of the real world which depend critically upon spatial relationships.

Another problem related to spatial resolution also arises from the approach used here. Consider an area with a number of nonattainment receptors and assume that roads in the vicinity of each would need to be controlled in reality. By choosing a single receptor in the rollback approximation, the costs for road controls maybe underestimated, because only that fraction of the roads affecting that single receptor are included in the estimation of costs. Those fractions affecting other nonattainment receptors are not included. In regard to this difficulty, paved municipal roads were candidates for control in each nonattainment area in counties with more than one such area. In such cases, the strategy development procedure and costs were developed assuming that a different effective fraction of paved municipal roads was appropriate to each area. However, in projecting future air quality only one effective fraction was assumed to affect a given receptor of interest.

Formalism. Following Eqs. 2.2.32 and 2.2.33 which summarize the adjustments made the base-year TSP area source inventory and the transformation to an estimate of base-year emissions of PM10, we may write

$$\hat{Q}_A = \hat{Q}_P + \hat{Q}_U + \hat{Q}_O \tag{3.1.20}$$

where the explicit dependence on pollutant can be dropped. Further, let

α = the fraction of total county-wide emissions from paved municipal roads assumed to affect a given receptor,

β = the fraction of area source emissions from unpaved municipal roads and other categories assumed to affect a given receptor,

γ = the fraction of area source emissions from unpaved municipal roads and other categories assumed to grow in proportion to population, and

$f = (1 + g_{pop})^{\Delta t}$ = the population growth factor Δt years after the base year

where

g_{pop} = the growth rate (fraction per year) for the appropriate state.

Then if $Q^{eff}(0)$ is the fraction of base-year area source emissions affecting the receptor of interest:

$$\begin{aligned} Q^{eff}(0) &= \text{effective fraction of paved municipal road emissions} \\ &\quad + \text{effective fraction of remaining emissions} \\ &= \alpha\hat{Q}_P + \beta(\hat{Q}_U + \hat{Q}_O). \end{aligned} \tag{3.1.21}$$

The first term in Eq. 3.1.21 for the effective fraction of paved roads will grow with population, but only a fraction γ of the second term will grow. Therefore, after Δt years

$$\begin{aligned} Q^{eff}(\Delta t) &= \alpha\hat{Q}_P f + \beta\gamma(\hat{Q}_U + \hat{Q}_O)f + \beta(1 - \gamma)(\hat{Q}_U + \hat{Q}_O) \\ &= \alpha Q_P f + \beta(\hat{Q}_U + \hat{Q}_O)(1 - \gamma + \gamma f) \\ &= \alpha\hat{Q}_P f + \beta(\hat{Q}_A - \hat{Q}_P)(1 - \gamma + \gamma f) \end{aligned} \tag{3.1.22}$$

using Eq. 3.1.20. In practice, the adjusted total area source emissions and paved road emissions, $\hat{Q}_A$ and $\hat{Q}_P$, were included in the area source inventory and the last form of Eq. 3.1.22 was used to project area source emissions given a particular set of input values from the parameters α, β, and γ. The base analysis scenarios had $\alpha = \beta = .01$ and $\gamma = 0$, that is, 1% of all area sources including paved municipal roads were assumed to affect the receptor of interest and only paved municipal roads among all area sources were permitted to grow.

3.2 PROJECTING FUTURE AIR QUALITY

After future emissions have been projected, an estimate of the corresponding air quality must be made in order to determine the extent of anticipated nonattainment. This section describes the procedures used to perform these tasks, which correspond to boxes 6, 9, and 10 in Fig. 1.1. These procedures are some of the functions carried out by the MARGIN program in Fig. 1.2A. The projection of air quality based on emissions requires the use of an air quality model. Rollback is widely used in county-level analyses that are national in scope because the calculations involved are simple and require a minimum of data. Simple rollback was the model of choice for air quality projections in the EEA system[2] and in this work, since it was already incorporated within the MARGIN code. In anticipation of the use of a modified form of rollback in developing coupling coefficients and the control strategy, Sec. 3.2.1 provides a general discussion of rollback models and coupling coefficients. The use of simple rollback to project air quality is described in Sec. 3.2.2 and the choice of the most restrictive situation for detailed analysis is described in Sec. 3.2.3.

3.2.1 Rollback Models and Coupling Coefficients

Rollback is a term used to refer to a class of air quality models which assume that the total pollutant concentration at receptor i can be found from[12]

$$X_{il} - b_l = \sum_j c_{ij} Q_j \qquad (3.2.1)$$

where

X_{il} = the concentration at receptor i for averaging time l,

Q_j = the emissions rate for source j,

b_l = the background for averaging time l and

c_{ij} = a constant for each source and receptor.

This equation is assumed to hold at all times, that is, the coefficients c_{ij} are assumed appropriate for use in the base year and all projection years. In the base year, the observed air quality is X^o_{il} and we may write

$$X^o_{il} - b^o_l = \sum_k c_{ik} Q^o_k \tag{3.2.2}$$

where Q^o_k and b^o_l are the emissions and background in the base year. Dividing Eq. 3.2.1 by Eq. 3.2.2 and rearranging:

$$X_{il} - b_l = \sum_j \left(\frac{c_{ij}[X^o_{il} - b^o_l]}{\sum_k c_{ik} Q^o_k} \right) \cdot Q_j. \tag{3.2.3}$$

Since the c_{ij}'s occur in both the numerator and denominator of Eq. 3.2.3, any quantity proportional to them may be substituted for them and the equation will still be true. The c_{ij}'s are frequently assumed to be independent of the receptor and to depend only on the physical properties of the source, for example, stack height and plume rise. Calling these source-specific factors w_j and assuming that $w_j \propto c_{ij}$:

$$X_{il} - b_l = \sum_j \left(\frac{w_j[X^o_{il} - b^o_l]}{\sum_k w_j Q^o_k} \right) \cdot Q_j. \tag{3.2.4}$$

In terms of coupling coefficients, the air quality contribution of a source j to receptor i is given by

$$X_{ijl} = T^l_{ij} \times Q_j \tag{3.2.5}$$

where

X_{ijl} = concentration for averaging time l at receptor i due to emissions from source j,

Q_j = emission rate for source j as above, and

T^l_{ij} = the corresponding coupling coefficient by definition.

The total concentration at receptor i (χ_{i1}) is given by the sum of contributions from all sources plus the background, which may be considered as the contribution of all sources not considered explicitly:

$$\chi_{i1} = b_1 + \sum_j T^1_{ij} \times Q_j. \tag{3.2.6}$$

Comparison of Eqs. 3.2.4 and 3.2.6 yields a rollback coupling coefficient

$$T^1_{ij} = \frac{w_j}{\sum_k w_k Q^o_k} [\chi^o_{i1} - b^o_1]. \tag{3.2.7}$$

Substitution of Eq. 3.2.7 into Eq. 3.2.6 with base-year values for Q_j and b_1 results in a concentration $\chi_{i1} = \chi^o_{i1}$ as desired.

Taking $w_j = 1$ in Eq. 3.2.7 removes the dependence of the coupling coefficient on the source j. That is,

$$\chi_{ij1} = T^1_i \times Q_j, \ (w_j = 1), \tag{3.2.8}$$

implying that all sources have the same impact per unit of emissions at a particular receptor i regardless of the physical characteristics of the sources or their spatial relationships with the receptor. For this case ($w_j = 1$); Eq. 3.2.6 can be rewritten using Eq. 3.2.7:

$$\chi_{i1} - b_1 = \frac{\sum_j Q_j}{\sum_k Q^o_k} [\chi^o_{i1} - b^o_1] \tag{3.2.9}$$

or

$$\frac{\chi_{i1} - b_1}{\chi^o_{i1} - b^o_1} = \frac{\sum_j Q_j}{\sum_k Q^o_k} = \frac{Q_{TOT}}{Q^o_{TOT}} \tag{3.2.10}$$

where Q^o_{TOT} and Q_{TOT} are the total emissions in the base year and the projection year, respectively. This is the most familiar form of rollback in which the excess of air quality above background ($\chi_{i1} - b_1$) varies in proportion to the total emissions in the analysis area. Other possible choices can also be made for w_j. For example, the maximum ground-level concentration due to a given source varies inversely with some power of the stack height suggesting that $w_j = (1/h_j)^n$ where h_j is an appropriately chosen stack height and n an

appropriate exponent might offer a reasonable choice (see Sec. 6.2.2 for a discussion of this concept). As discussed in Sec. 4.1, a value of n=1 was used in this work for estimating source-specific coupling coefficients; as discussed in the following section, a value of n=0 was used in making the air quality projections.

It should be noted that the rollback coupling coefficients as calculated by Eq. 3.2.7 do not contain an explicit dependence on the distance between the source j and the receptor i. It is possible to include a spatial dependence by choosing the factors c_{ij} properly (see Ref. 12). However, both forms of rollback used in the EEA model and in this work used by w_j's which were either independent of the source ($w_j = 1$) or which depended only on the effective release height associated with the source.

3.2.2 Air Quality Projections

The EEA model was set up to make air quality projections for only a single year, the year in which the standards were to be attained. This was also assumed to be the year in which the control strategy was implemented. Any controls required for attainment were put on in that year, and hence it was called the implementation year. This approach is purely static; it does not look beyond the implementation year to consider maintenance of the standard. If growth were sufficient to make total emissions increase beyond the implementation year with a concomittant increase in pollutant concentrations, then at some point in time, nonattainment would result. This work considered maintenance of the standards out to 1995. Implementation years were taken to be 1987 for TSP standards and 1989 for PM10 standards. In fact, both the implementation year and the maintenance year were specified in the scenario file (file 4.3 in Fig. 1.2A) as one of the inputs to the computer programs permitting the two projection years to be changed. In addition, a switch in the scenario file could be set to turn off the maintenance feature, returning the system to the earlier EEA form in which air quality was projected for only a single implementation year.

The procedure for making air quality projections was relatively simple and was accomplished by the use of county-wide rollback ($w_j = 1$). From Eq. 3.2.10:

$$\chi_{i1} = b_1 + \frac{Q_{TOT}}{Q^o_{TOT}} (\chi^o_{i1} - b^o_1). \qquad (3.2.11)$$

In this equation, Q^{o}_{TOT} is the total county emissions in the base year and Q_{TOT} is the total county emissions for the projection year of interest. Both totals include area source emissions corrected for the effective fractions α and β in Eq. 3.1.22. As discussed when these factors were introduced, their introduction was an attempt to simulate to some extent the limited effective range believed to be associated with area sources having low effective release heights. No such considerations were applied to point sources which are equally effective at all receptors regardless of the source-receptor distance. It should also be noted that in a county with several analysis areas, the same values of Q_{TOT} and Q^{o}_{TOT} were applied in each area i. The same values were also applied to all averaging times "1" of interest. Since the standards of interest were all either annual averages or 24-hour extreme values, the implicit assumption has been made that the emission rates appropriate to both the annual and 24-hour periods are equal. Put another way, the assumption has been made that peaks in total emissions are not correlated with 24-hour extremes in concentrations so that for purposes of long term projections, the use of average emission rates is an acceptable procedure.

One change was introuduced into Eq. 3.2.11 to account for the tailpipe emissions of PM10 from vehicles powered by diesels. Diesels comprise a negligible fraction of the base-year (1978) particulate inventory and were probably not even considered when the base-year area source inventory was developed. Diesels are expected to penetrate the vehicle fleet to a significant degree over the next 15 years and they emit far more PM10 from their tailpipes than conventional vehicles. Since diesels were not included in the base-year inventory, the projections of both TSP and PM10 would be incorrect to the extent that diesels would affect the receptor of interest. If diesels replace conventional vehicles without altering the vehicle miles traveled or the split between urban and rural travel, the estimates of reentrained road dust emissions in the inventory should be independent of the presence or absence of diesels from the vehicle fleet, neglecting the possible second-order effect of increased reentrained road dust due to tailpipe emissions from diesels settling out and causing increased dust loadings on roadways. In addition, no controls were to be applied directly to diesel tailpipe emissions during strategy development. Diesel tailpipe emissions could thus be considered an emission not included in Q_{TOT} and their air quality impact could be included in the background term b_1. The diesels would have no contribution in the base year. The background b_1 would then be given by:

$$b_l = b_l^o + d_l^t \qquad (3.2.12)$$

where

b_l^o = the background value obtained from the base-year air quality file or the background default file and

d_l^t = the concentration due to tailpipe emissions of PM10 from diesels in year t ($d_l^o = 0$).

A switch in the scenario file permitted the calculation of the background concentrations b_l either with or without the additional concentrations from diesel tailpipe emissions. The diesel contributions were calculated by EPA on a county-by-county basis for the four required averages (GEOA, ARITHA, OB24, and EX24) for 1987, 89, and 95, the diesel contributions in the base year and 1985 being considered negligible. The file containing the diesel data is not shown in Fig. 1.2 but may be considered included within the background file 4.2. The base analysis scenarios were run without any contributions from diesels.

With this change included in the definition of the background concentration, the projection of air quality was made applying Eq. 3.2.11. The values of Q_{TOT}^o and Q_{TOT} were available from the county-level growth file (file 4.1 in Fig. 1.2A). The base-year air quality concentrations came from file 4.4.* At this point in the processing flow, the projections were made for the:

- Pollutant of interest, PM10 or TSP,
- The implementation year, 1987 for TSP or 1989 for PM10, and the maintenance year, 1995, and
- The averaging time or times, 24-hour or annual, of interest

as specified in the scenario being considered. Projections were eventually required for other years and were made using a procedure described later. For historical reasons, projections were only made for the maintenance and implementation years in the MARGIN program. At this point, projections of future air quality were available for each analysis area for two years and the one or two averaging times appropriate to the standard of interest. The next task was to choose the most restrictive projected situation for development of the control strategy.

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*As noted previously, the conversion of TSP concentrations to PM10 concentrations actually occurred in the MARGIN program.

3.2.3 Binding Year and Binding Averaging Time

Procedure

Depending upon the particular scenario being analyzed, there were either two or four projected pollutant concentrations for each analysis area. If all projected concentrations were at or below the corresponding standards, the area was considered to be in attainment and no additional processing of that area was undertaken. That is, if

$$\chi_{il}^{t} \leq s_l \tag{3.2.13}$$

where

s_l = the value of the standard for averaging time l and

χ_{il}^{t} = the projected concentration in area i for year t and averaging time l

for all l and t, the area i was eliminated from the process of strategy development and included among the attainment areas in the final summaries. No costs would be incurred in such areas. In Eq. 3.2.13, the superscript t has been added to the notation of Sec. 3.2.2 to take explicit recognition of different projection years.

In nonattainment areas, the combination of year and averaging time having the greatest "margin" above the standard was chosen as the basis for development of the control strategy. The concept of the margin was used in the EEA system to choose between two averaging times in the same year.[2] With the introduction of maintenance beyond the implementation year in this work, the concept was extended to include consideration of the projection year as well as the averaging time.

The margin M_l^t for a projection year t and averaging time l was defined by

$$M_l^t = \frac{\chi_l^t - s_l}{s_l - b_l^t} \tag{3.2.14}$$

where the explicit dependence of χ_{il}^{t} on the receptor i has been dropped to simplify the notation. No confusion should result, as the analysis proceeded independently for each area and only one receptor was considered in

each area. Margins that are zero or negative correspond to situations in which the standard is being attained. Operationally, an area of all of whose margins were zero or negative was dropped from further analysis. If at least one margin was positive, the area was retained for further analysis. The largest margin and the associated year and averaging time were identified as the binding conditions and the air quality reduction $\Delta\chi_r$ needed for attainment of the standard for the binding averaging time L in the binding year T was calculated:

$$\Delta\chi_r = \chi_L^T - s_L. \tag{3.2.15}$$

These values of $\Delta\chi_r$ were used during development of the control strategy to determine the controls necessary to attain the binding standard in the binding year. The choice of the binding conditions was based upon considerations of air quality. The fundamental concern which this choice attempts to address is the difficulty of obtaining the overall reduction in emissions needed for attainment. As noted in the following discussion, attaining the required emission reductions may be more difficult under conditions other than those corresponding to the largest air quality margin.

Discussion

In this subsection a superscript t has been used to identify the year and the subscript i for the area has been deleted.

Concentration projections were made by Eq. 3.2.10 which may be rearranged to give:

$$\chi_1^t = b_1^t + \frac{Q_{TOT}^t}{Q_{TOT}^o}(\chi_1^o - b_1^o) \equiv b_1^t + F^t(\chi_1^o - b_1^o). \tag{3.2.16}$$

The difference between the projected concentration and the standard s_1 is then

$$\chi_1^t - s_1 = F^t(\chi_1^o - b_1^o) - (s_1 - b_1^t). \tag{3.2.17}$$

Dividing by $(s_1 - b_1^t)$ and using the definition of the margin M_1^t (Eq. 3.2.14) yields

$$M_1^t = F^t \frac{X_1^o - b_1^o}{s_1 - b_1^t} - 1. \qquad (3.2.18)$$

To determine whether attainment is achieved by the strategy, it is necessary to consider how the effect of a control strategy on the projected concentration was modeled. Assume that a control strategy is applied in the year t. Using carets to denote the value of quantities after the application of controls, we can write

$$\Delta X_{j1}^t = X_{j1}^t - \hat{X}_{j1}^t = T_j^1(Q_j^t - \hat{Q}_j^t) \equiv T_j^1 \Delta Q_j^t \qquad (3.2.19)$$

for the air quality change from source j due to the application of the strategy where Eq. 3.2.5 has been used to calculate the concentrations. The total concentration change ΔX_1^t can be found by summing the individual ΔX_{j1}^t. Looking ahead to the use of weighted coupling coefficients in the development of the strategy, this total change can be written as

$$X_1^t - \hat{X}_1^t = \Delta X_1^t = \sum_j T_j^1 \Delta Q_j^t = \frac{\sum_j w_j \Delta Q_j^t}{\sum_k w_k Q_k^o} (X_1^o - b_1^o) \equiv A^t (X_1^o - b_1^o) \qquad (3.2.20)$$

where Eq. 3.2.7 has been used for the weighted coupling coefficients. The purpose of the control strategy is to reduce the concentration $\hat{X}_1^t$ to at least the level of the corresponding standard s_1. Let

$\hat{A}_1^t$ = value of A^t required for attainment of the standard for averaging time 1 in year t.

Then

$$X_1^t - s_1 = \hat{A}_1^t (X_1^o - b_1^o) \qquad (3.2.21)$$

from which it follows that

$$\frac{X_1^t - s_1}{s_1 - b_1^t} = \hat{A}_1^t \frac{X_1^o - b_1^o}{s_1 - b_1^t} = \hat{A}_1^t \frac{(X_1^o - s_1) + (s_1 - b_1^o)}{s_1 - b_1^t}.$$

Dividing numerator and denominator by $(s_1 - b_1^o)$, the preceeding expression can be rewritten as

$$\frac{\chi_1^t - s_1}{s_1 - b_1^t} = \hat{A}_1^t \frac{M_1^o + 1}{1 - D_1^t} \tag{3.2.22}$$

where the time variation in the background b_1^t has been ascribed to the diesel emissions d_1^t so that

$$b_1^t = b_1^o + d_1^t \tag{3.2.23}$$

and D_1^t has been defined by:

$$D_1^t = \frac{d_1^t}{s_1 - b_1^o} \; ; \; D_1^t = 0 \text{ when diesels are not included.} \tag{3.2.24}$$

The left-hand side of Eq. 3.2.22 is by definition the margin M_1^t so that

$$\hat{A}_1^t = (1 - D_1^t)\left(\frac{M_1^t}{M_1^o + 1}\right). \tag{3.2.25}$$

The strategy will work for a particular year m and all averaging times 1 if the value of A^m generated by the strategy (A^m_{strat}) is equal to or greater than all of the required $\hat{A}_1^m$, that is, if

$$A^m_{strat} \geq \hat{A}_1^m \text{ for all 1 and in the year m.} \tag{3.2.26}$$

Using Eq. 3.2.18 for the margins, Eqs. 3.2.23 and 3.2.24 to show the diesel contributions explicitly, and noting that $F^o = 1$, the expression for $\hat{A}_1^t$ may be rewritten:

$$\hat{A}_1^t = \frac{F^t\left(\frac{\chi_1^o - b_1^o}{s_1 - b_1^o}\right) - (1 - D_1^t)}{\left(\frac{\chi_1^o - b_1^o}{s_1 - b_1^o}\right)}. \tag{3.2.27}$$

Noting from Eq. 3.2.14 that

$$M_1^o + 1 = \frac{\chi_1^o - b_1^o}{s_1 - b_1^o}, \tag{3.2.28}$$

Eq. 3.2.27 becomes

$$\hat{A}_1^t = F^t - \frac{1 - D_1^t}{M_1^o + 1}. \tag{3.2.29}$$

Diesels Off. Consider first the case with no diesels, $D_1^t = 0$. In this case

$$M_1^t = F^t(M_1^o + 1) - 1 \text{ (no diesels)} \tag{3.2.30}$$

by Eq. 3.2.18 because $b_1^t = b_1^o$, there being no time dependent contribution from diesels to the background. The maximum value of M_1^t will occur for the year T in which F^t has its maximum value F^T and for the averaging time L for which M_1^o has its maximum value M_L^o. The values of T and L would of course be determined by picking the maximum margin from among those considered. For these values of T and L, Eq. 3.2.29 gives ($D_1^t = 0$):

$$\hat{A}_L^T = F^T - \frac{1}{M_L^o + 1} \geq \hat{A}_1^t \text{ for all t and 1.} \tag{3.2.31}$$

Since F^T and M_L^o are both maxima, the value of $\hat{A}_L^T$ in Eq. 3.2.31 corresponding to the maximum margin is also a maximum. The model picks a pair of binding conditions by looking at the margins and picking the maximum. Then, an attempt is made to develop a strategy by controlling unreplaced sources. If an attainment strategy can be developed, the A_{strat}^T corresponding to the strategy is at least as large at $\hat{A}_L^T$:

$$A_{strat}^T \geq \hat{A}_L^T \geq \hat{A}_1^T. \tag{3.2.32}$$

Thus, the strategy will work for all other averaging times in the binding year. However, once another year s is considered, it cannot be assumed that the strategy will provide attainment in that year even though $A_{strat}^T \geq \hat{A}_1^s$, because sufficient emission reductions may not be available in the year s.

If s occurs later in time than T, some of the sources controlled by the strategy as well as some of the sources unreplaced in year T are replaced by sources at new-source levels of control. Additional growth at new-source levels has also occurred in the years between T and s. It is by no means certain that the emission reductions available from sources controlled by the strategy and not replaced between T and s will be sufficiently large to reach attainment. In other words, the emissions reductions available from sources controlled by the strategy in year T and not replaced by the year s may correspond to a value of A_1^s such that $A_1^s < \hat{A}_1^s$ even though $\hat{A}_L^T > \hat{A}_1^s$. In cases where such unanticipated nonattainment occurred, control of additional previously uncontrolled sources might have resulted in attainment. Such a dynamic, year-by-year approach was not possible using the earlier, static model developed for consideration of a single projection year.

Two additional points need to be made. First, the procedure used in the analysis system considered only the implementation and maintenance years and the averaging times corresponding to the standards being considered in choosing a binding year and averaging time. As will be discussed later, air quality estimates were also requested for the other years and averaging times. The procedure employed clearly does not guarantee attainment for these additional years and averaging times.

The second point relates to Eq. 3.2.17 and 3.2.20. Inspection of these equations shows that the unweighted coupling coefficients used in projecting future air quality for purposes of choosing L and T can be different than those used in developing the control strategy where weighted coupling coefficients were used. The demonstration in this subsection shows that despite this difference that when diesels are shut off, an attainment strategy developed for the binding year and averaging time will be an attainment strategy in the binding year for the other averaging times whose margins were considered.

Diesels On. Turning on the diesels is equivalent to having a time-dependent background and the remarks in this subsection are generally valid for all cases for which the total background can be written as $b_1^t = b_1^o + d_1^t$ where b_1^o is the value of the background in the base year and d_1^t describes the dependence of the background on time.

With diesels on, the term D_l^t in Eq. 3.2.27 cannot be taken as zero for all t and l and the form of M_l^t corresponding to Eq. 3.2.30 is

$$M_l^t = \frac{F^t(M_l^o + 1)}{1 - D_l^t} - 1 \qquad (3.2.33)$$

which is seen to reduce to Eq. 3.2.30 when $D_l^t = 0$. Combining Eqs. 3.2.33 and 3.2.29 it can be shown that

$$\hat{A}_l^t = \frac{(1 - D_l^t)}{M_l^o + 1} M_l^t. \qquad (3.2.34)$$

This equation shows that $\hat{A}_L^T$ corresponding to the maximum margin M_L^T is not necessarily a maximum unless

$$\frac{1 - D_L^T}{M_L^o} \geq \frac{1 - D_l^t}{M_l^o} \text{ for all l and t.}$$

There is no reason to expect this to be the case. The denominator of the critical factor does not depend on time and $D_l^t \propto d_l^t$ for a fixed averaging time. Since diesel emissions could be less in some year t than they are in year T, the above inequality may not be satisified. Even with the diesels on it is still true that an attainment strategy developed for the binding averaging time T in the binding year L will guarantee attainment for the other averaging time in the binding year. For a fixed year T, Eq. 3.2.33 shows that the maximum margin will occur for a maximum of the factor $(M_l^o + 1)/(1 - D_l^T)$ and hence that corresponding $\hat{A}_L^T$ given by Eq. 3.2.34 will also assume its maximum value for the year T for the averaging time L.

4 CONTROL STRATEGY DEVELOPMENT

At this point in assessing the impacts associated with a particular standard, all the nonattainment areas among the analysis areas had been identified. For each area, the binding year, binding averaging time, and the air quality reductions required for attainment were available. The strategy was developed in several stages. First, for each source in a nonattainment area, a set of control options and the associated reductions in emissions achieved by each option were determined. Information related to the costs of applying each option was also developed. Then, following the procedure for choosing options described below, the options were applied one at a time until either the required overall air quality reduction was obtained or no additional options were available. In order to determine the concentration changes associated with the emission reductions, coupling coefficients were calculated as described in Sec. 4.1. Then the list of options available to each source was developed as discussed in Sec. 4.2. Section 4.3 provides a discussion of the procedure used in selecting the control strategy.

4.1 COUPLING COEFFICIENTS

The procedures described in this section relate to box 11 in Fig. 1.1 and are carried out by the ROLLBACK program in Fig. 1.2B.

Prior to the calculation of the coupling coefficients, the required air quality reductions ($\Delta\chi_r$) were screened both in the earlier model[2] and in this work. Areas needing less than 1 $\mu g/m^3$ of air quality reduction to meet the standard ($\Delta\chi_r < 1$) were considered as already being in attainment and were not analyzed further. This 1 $\mu g/m^3$ screen was felt to be reasonable in view of inaccuracies in the rollback model and the data. In addition, discussions with EPA indicated that areas close to the standard might not be required to implement control strategies without further evaluation of existing air quality and that tracking air quality to determine the need for additional controls might be a more likely situation in such areas. The 1 $\mu g/m^3$ screen was considered to be a reasonable way of simulating this eventuality.

In the areas remaining after this screen, rollback coupling coefficients were calculated for each source using Eq. 3.2.7 with the source-specific weight factor w_j given by

$$w_j = \frac{10}{H_j} \tag{4.1.1}$$

so that the coupling coefficients were given by

$$T_j^1 = \frac{(10/H_j)}{\sum_k (10/H_j)Q_k^o} \left[\chi_1^o - b_1^o\right] \tag{4.1.2}$$

where H_j is the effective release height in meters (stack height plus plume rise) associated with the source j and 10 m is a normalizing factor. This form of weighting factor was used in the earlier model[2] and was carried forward to this work. All area sources including paved roads and nontraditional fugitive sources were assumed to have release heights of 10 m, that is, $w_j = 1$ for these sources. Plume rise for stack sources was calculated by the BEH072 algorithm employed in several EPA dispersion models. The algorithm is the Sept. 1979 implementation of the Brigg's equations for plume rise. The wind speed was assumed to be 2.5 m/sec, just above the minimum wind speed consistent with C stability, the stability class for which Ref. 2 claims that Eq. 4.1.1 is a reasonable approximation of the dependence of the maximum concentration on effective release height.* The parameters needed for calculating H_j (physical stack height, stack diameter, effluent temperature, and effluent velocity) were available in the point source emissions inventory. Sources with insufficient data for the calculation of coupling coefficients were not considered as candidates for control during strategy development.

Coupling coefficients were not calculated for unpaved roads and other area sources because these sources were never considered as candidates for control, because controls were either unavailable or could not be costed for these sources. Emissions from these two area source categories were included in the demoninator of Eq. 4.1.2 which must include emissions from all sources, not just those to be considered as candidates for control. For the area source categories, the effective emissions given by Eq. 3.1.21 were used in the denominator of Eq. 4.1.2 to maintain consistency between the area source emissions used in projecting countywide emissions and air quality and the area source emissions used in calculating the coupling coefficients.

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*In conjunction with this work, it was determined that a different formulation of the factor w_j would have been more defensible than the $(10/H_j)$ factor used in the earlier model. This point is discussed in Sec. 6.2.2 on potential problems.

4.2 CONTROL OPTIONS

The operations discussed in this subsection correspond to box 12 in Fig. 1.1 and are accomplished by the CONCOST program in Fig. 1.2B.

For each source in a nonattainment area, a list of source-specific control options available for selection during strategy development was prepared. The options were screened to eliminate undesirable options that would increase emissions or not be cost-effective. Figure 4.1 illustrates the steps involved for a single source. This figure does not represent the actual processing steps in CONCOST but does represent the concepts implemented by the code. Candidate options were selected for each source from among the generic options (box 13 in Fig. 1.1 and file 7.2 in Fig. 1.2B) This selection was based upon the SCC of the source being considered.* Sources whose SCC's did not appear on the list of generic options were not considered as candidates for control during strategy development. The efficiencies of the candidate generic options were compared to the inventoried efficiency for the pollutant of interest. All options less efficient that the current controls were not considered further ensuring that all options finally considered available would represent a decrease over current emission levels. Thus at no time was a relaxation of current particulate controls considered.

With the cost parameters from the generic options file and the appropriate operating parameters from the emissions inventory, source-specific capital and O&M costs for the remaining options were calculated using Eq. 2.3.1. For paved municipal roads, the appropriate operating rate was the number of road miles, RM_{PAV}. Estimates of RM_{PAV} were made by:

$$RM_{PAV} = \alpha \left[\frac{(VMT_u + VMT_r)}{R(state)} \right], \qquad (4.2.1)$$

where

α = the effective fraction for municipal roads defined in Sec. 3.1,

VMT_u, VMT_r = urban and rural vehicle-miles traveled by county as discussed in Sec. 3.1, and

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*Nonstandard three-digit SCC codes were used to identify nontraditional fugitive and minicipal road sources.[2]

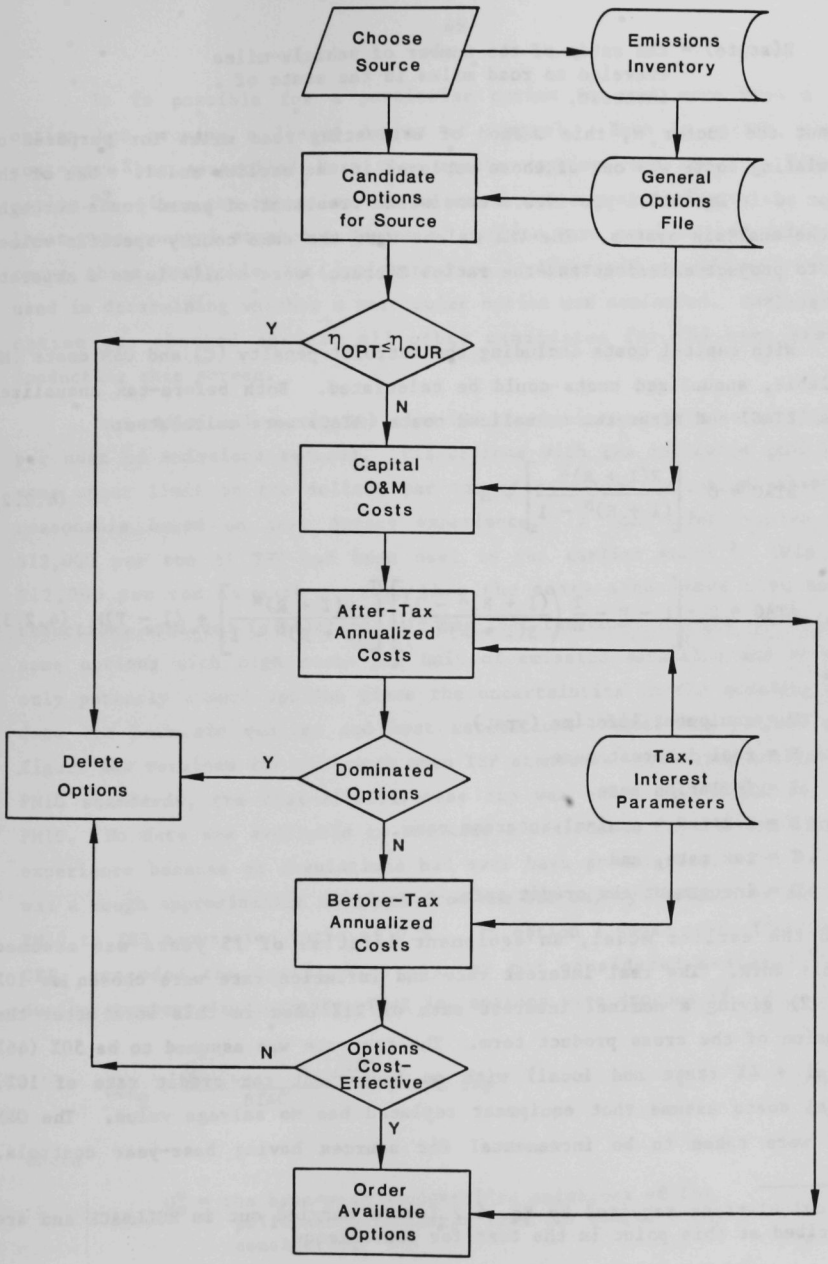


Fig. 4.1 Available Control Options

R(state) = the ratio of the number of vehicle-miles traveled to road miles in the state of interest.

Without the factor α, this method of estimating road miles for purposes of calculating costs was one of those employed in the earlier model.[2] Use of the factor α in Eq. 4.2.1 provides a consistent treatment of paved roads throughout the analysis system. The VMT values were the same county-specific values used to project emissions and the ratios R(state) were available as a separate data set.*

With capital costs including the retrofit penalty (C) and O&M costs (M) available, annualized costs could be calculated. Both before-tax annualized costs (BTAC) and after-tax annualized costs (ATAC) were calculated:

$$BTAC = C \cdot \left[\frac{R(1 + R)^N}{(1 + R)^N - 1}\right] + M \qquad (4.2.2)$$

and

$$ATAC = C \cdot \left[1 - D - \frac{T}{N}\left(\frac{(1 + B)^N - 1}{B(1 + B)^N}\right)\right]\left[\frac{R(1 + R)^N}{(1 + R)^N - 1}\right] + (1 - T)M \qquad (4.2.3)$$

where

N = equipment lifetime (yrs.)

R = real interest rate,

I = inflation rate,

B = I+R+IxR = nominal interest rate,

T = tax rate, and

D = investment tax credit rate.

As in the earlier model, an equipment lifetime of 15 years was assumed in this work. The real interest rate and inflation rate were chosen as 10% (Ref. 2) giving a nominal interest rate of 21% used in this work after the inclusion of the cross product term. The tax rate was assumed to be 50% (46% federal + 4% state and local) with an investment tax credit rate of 10%. Capital costs assume that equipment replaced has no salvage value. The O&M costs were taken to be incremental for sources having base-year controls.

*The calculations required by Eq. 4.2.1 were carried out in ROLLBACK and are described at this point in the text for convenience.

It is possible for a particular option to cost more than a second option but provide a lesser degree of control. Such an option, one that cost more but controlled less than another option, was termed a "dominated option."[2] Since the intention was to develop an approximation to the least-cost control strategy, dominated options were screened and deleted from among those available for implementation. After-tax annualized costs were used in determining whether a particular option was dominated. Each candidate option was checked against all other candidates for the same source in conducting this screen.

One additional screen was also run to eliminate options with high costs per unit of emissions reduced. Discussions with EPA indicated that placing some upper limit on the dollars per ton of emissions reduction achieved was reasonable based on past Agency experience. A cost-effectiveness cap of $12,000 per ton of TSP had been used in the earlier model.[2] This cap of $12,000 per ton is much greater than the costs associated with emission reductions achieved in practice. It was felt reasonable to let the model pick some options with high costs per unit of emission reduction and screen out only patently absurd options given the uncertainties in the modeling and the data for both air quality and cost estimation. Thus, the $12,000 per ton figure was retained for this work when TSP standards were being analyzed. For PM10 standards, the cost-effectiveness cap was taken as $21,800 per ton of PM10. No data was available to estimate a reasonable cap for PM10 from past experience because no regulations had ever been promulgated. The value used was a rough approximation obtained from the TSP cap by division by the ambient PM10 to TSP conversion ratio of 0.55. An option i whose cost-effective ratio CER_i exceeded the appropriate cap was not considered available for use during strategy development. That is, options were dropped if

$$CER_i \quad \frac{Q_o^u(\eta_{opt} - \eta_o)/100}{BTAC_i} > \text{C/E cap} \qquad (4.2.4)$$

where

Q_o^u = the base-year uncontrolled emissions of the pollutant of interest from the source being considered,

η_{opt}, η_o = the control efficiencies of the option and the base-year control efficiency, respectively, and

C/E cap = the appropriate cost-effectiveness cap.

As shown in Eq. 4.2.4, the screen for cost-effectiveness looked at the total BTAC for each option and considered the incremental reduction of that option over base-year levels of control. The test for each option for a particular source was thus an incremental test with respect to base-year controls, not incremental with respect to another option. In particular, this test for cost-effectiveness did not consider the incremental cost-effectiveness based on the order in which multiple options for a single source would be applied during strategy development. After screening for cost-effectiveness, any remaining options were considered available for use during strategy development. These options were ordered by increasing after-tax annualized cost. Thus, associated with each source in a nonattainment area having any available options was a list of increasingly costly, cost-effective options each more efficient than base-year controls and each more efficient than all earlier options in the list. These lists were contained in file 8.2 of the computer system shown in Fig. 1.2B. Given the structure of the earlier list of generic options, the list of available options for any source could contain at most two options for TSP scenarios and at most three options for PM10 scenarios.

4.3 IMPLEMENTATION OF CONTROLS

This subsection describes the actual development of a low-cost control strategy (box 14 in Fig. 1.1) as carried out in the computer program LEASTCOST in Fig. 1.2B. The process used to select the specific options implemented is described in Sec. 4.3.1. The corresponding cost and impact calculations are described in Sec. 4.3.2. Section 4.3.3 provides a short discussion.

4.3.1 Selection of Options

At this point it is useful to recall that three years are involved in the process described heretofor: the base year, the implementation year, and the maintenance year and that the binding year (BY) may be either the implementation year (IY) or the maintenance year (MY). That the binding year may differ from the year in which controls are assumed to be applied, the IY, must be taken into account when the effects of applying controls are calculated.

The procedure for choosing the particular set of control options comprising the strategy is summarized in Fig. 4.2 for a single nonattainment area. The process its iterative; one option is chosen and implemented at each iteration. Briefly:

- The selection process begins with ordered lists of available options j for each source i, P_{ij}. These lists contain increasingly costly, cost-effective options each more efficient than base-year controls and each more efficient than all preceeding options on the list.
- From among the options for each source, the cheapest remaining option P_{iL} is considered, one option for every source with any options not yet implemented on a particular iteration.
- Based on incremental air quality improvement and incremental before-tax annualized costs, a cost-effectiveness parameter is calculated for each option P_{iL}. This parameter gives the $\$/\mu g/m^3$ of air quality improvement associated with the options under consideration.
- The option P_{IL} for source I having the smallest cost-effectiveness parameter is chosen for implementation and the associated change in the concentration reduction needed for attainment is calculated.
- If air quality is within 1 $\mu g/m^3$ of the standard, the process terminates with an attainment strategy. If not, the option P_{IL}, just implemented, is eliminated from the list of remaining options and the process is repeated.
- If on any iteration, all available options have been implemented and the required air quality reduction is still 1 $\mu g/m^3$ or greater, the process terminates with residual nonattainment.

The following paragraphs describe this process in more detail.

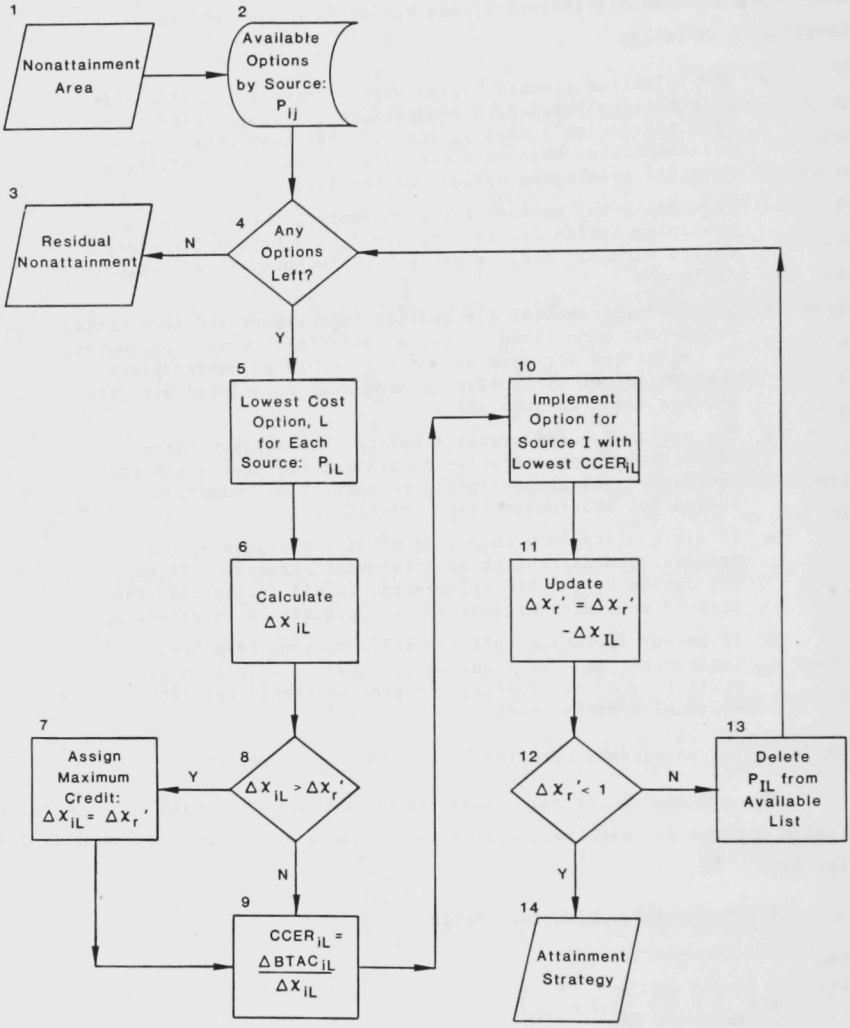
The process for a particular nonattainment area begins with a set of ordered options for each potentially controllable source in the area (box 2 in Fig. 4.2). If

P_{ij} = the j^{th} option for source i,

then

$$\left.\begin{array}{l} \eta(P_{in}) > \eta(P_{im}) > \eta_{oi} \\ ATAC(P_{in}) > ATAC(P_{im}) \end{array}\right\} \quad \text{if } n > m \qquad (4.3.1)$$

where η_{oi} is the base-year efficiency for source i from the emissions inventory. Equation 4.3.1 is the direct result of the procedure followed by CONCOST in selecting and ordering the available options as described in Sec.



NB: To simplify the notation, this figure does not distinguish between quantities calculated in the IY and similar quantities calculated in the MY.

Fig. 4.2 Control Strategy Development

4.2. For this work, the maximum value of j for any source was 3. (In this subsection, the specific pollutant of interest is not indicated by the notation. Since strategies involving both TSP and PM10 standards were not considered, no confusion should result from this omission.) At each iteration, the cheapest remaining option P_{iL} in terms of total after-tax annualized costs was identified for each source (box 5 in Fig. 4.2). Operationally, it was only necessary to choose the first option not already implemented for each source because the options were ordered by ATAC (see Eq. 4.3.1). For example, on the first iteration, L = 1 for all sources.

From among the set of remaining lowest cost options the one that had incrementally the cheapest per unit costs was chosen for implementation. This decision was made based on the ratio of the incremental air quality reduction to the incremental before-tax annualized cost associated with each candidate option and required several preliminary calculations.

Prior to describing these calculations it is convenient to define a factor ϕ_i^t such that

$$\phi_i^t \equiv (1 - K_i^t + bL_i^t + aM_i^t) \qquad (4.3.2)$$

where superscripts have been used to denote the particular year as in Sec. 3.2. Reference to Eqs. 3.1.12 and 3.1.15 shows that ϕ_i^t is just the fraction of each source assumed to emit at base-year levels in the year t. The time-dependence of ϕ_i^t is included in the factors K, L, and M which represent growth and replacement and hence depend upon time and also upon the SIC and state corresponding to the particular source i. These dependences have been indicated explicitly in Eq. 4.3.2. The first two terms represent the fraction of the source not replaced between the base-year and the year t. The third term represents that fraction of the source retired and replaced with new replacement growth but still emitting at base-year levels. The last term is the fraction of the source in year t that is new growth that has come on-line at base-year emission levels. For nonnegative growth and with all replacement and growth sources controlled to new source levels (a = b = o):

$$\phi_i^t = (1 - R_i^t).$$

Generally, relatively new sources emitting at efficient new source levels would probably be exempted from additional control during SIP development. To simulate this situation, this work assumed that only a fraction ϕ_i^{IY} of each candidate source would be subject to control during implementation of the strategy. In terms of the concept of many small sources introduced in Sec. 3.1.1, this procedure simulates the situation in which only base-year unreplaced and new growth and replacement sources not subject to new source controls would be considered for additional control during strategy development. Put another way, all sources not required to apply new source level controls were assumed to be candidates for control during strategy development.* The approach to strategy development used in this work thus parallels the so-called accommodative SIP approach (see, for example, Ref. 13) in which all controls are required to be applied prior to the scheduled attainment year, even when the greatest air quality constraint is expected in a later year due to growth projected between the attainment year and the later year. All controls in this work are applied in the implementation (scheduled attainment) year even when the binding year was the later maintenance year. In areas with residual nonattainment, no provision was made in this work to force attainment through the application of stringent controls to new growth and replacement sources already emitting at new source levels even when more efficient controls were considered during strategy development.

Returning to the calculations, the incremental emission reductions associated with the implementation of the options P_{iL} can now be calculated. After the first iteration, P_{iL} for a particular source need not be the first option in that source's list of available options. Calling the last previously applied option $P_{i,prev}$ and defining base-year controls as the "option" previous to the first listed candidate option; the incremental emission reduction in the implementation year is

$$\Delta Q_{iL}^{IY} = Q_i^{uo}[(\eta(P_{iL}) - \eta(P_{i,prev})] \cdot \phi_i^{IY}$$

$$\equiv \Delta Q_i^{o}(P_{iL}) \cdot \phi_i^{IY} > 0 \qquad (4.3.3)$$

*For the scenarios used in the Regulatory Impact Analysis, the value of "a" was taken as zero. Thus, all new growth sources were projected to emit at new source levels and were unaffected by the strategy.

where $\Delta Q_i^o(P_{iL})$ is the incremental emission reduction that would be achieved by option P_{iL} in the base year. With this last observation the equation states that the emission reduction achievable in the IY is the reduction achievable in the base year times the fraction of the source subject to control in the IY. Having the emission reductions, the concentration reductions can be calculated using the coupling coefficients in Eq. 4.1.2:

$$\chi_{iL}^{IY} = T_i^1 \cdot \Delta Q_{iL}^{IY} \tag{4.3.4}$$

where the averaging time "1" is chosen to correspond to the binding averaging time. These incremental emission reductions correspond to box 6 in Fig. 4.2. In the codes, the appropriate coupling coefficients and emissions information needed to calculate the $\Delta\chi_{iL}$'s were passed forward in the options file (file 8.2 in Fig. 1.2B).

A similar calculation was made of the incremental before-tax annualized cost associated with each P_{iL} in the implementation year in preparation for calculation of the cost-effectiveness parameters:

$$\Delta BTAC_{iL}^{IY} = [BTAC(P_{iL}) - BTAC(P_{i,prev})] \cdot \phi_i^{IY} \tag{4.3.5}$$

Equation 4.3.5 includes an important assumption: the cost of an option may be reduced by the controllable fraction factor ϕ_i^t to obtain a reasonable estimate of the cost. For a large number of sources for which ϕ_i^t reasonably represents the fraction of sources controllable, this assumption is reasonable. When applied to individual sources as was the case in this work, the assumption may not be as reasonable, because controls cannot be applied to fractions of sources and even if the fractional assumption is used for purposes of air quality calculations, it is not clear that the same fraction is appropriate for cost calculations. In discussions with EPA it was decided to use this assumption for costs, since it is reasonable when a large number of sources is involved and thus may be a reasonable assumption for estimating costs at the state or higher level of aggregation.

The cost-effectiveness of each option could then be taken as

$$\frac{\Delta BTAC_{iL}^{IY}}{\Delta\chi_{iL}^{IY}} = \frac{BTAC(P_{iL}) - BTAC(P_{i,prev})}{T_i^1 \cdot \Delta Q_i^o(P_{iL})}$$

as was done in the earlier model. The second form of this expression follows from Eqs. 4.3.3, 4.3.4, and 4.3.5. The factors ϕ_i^{IY} cancel and thus the cost-effectiveness ratio is independent of the choice of the implementation year. However, if this approach is taken, options producing concentration reductions greater than those required for attainment could have more attractive (lower) cost-effectiveness ratios than equivalently priced or cheaper options producing concentration reductions equal to those required for attainment. Consider for example, two options, 1 and 2, for two different sources. Table 4.1 presents a hypothetical situation which might occur during strategy development on an iteration for which a concentration reduction of R is required for attainment. Implementation of option 1 would just attain the standard whereas implementation of the more expensive option 2 would overshoot the standard. With the original unconstrained C/E ratios, option 2 having the lower C/E ratio would be implemented at a greater cost than option 1 which would also attain the standard. In discussions with EPA, it was decided that such situations should be avoided if possible and that in general, options should not appear more attractive simply by producing greater concentration reductions than required for attainment. Thus, the reduction used in calculating the C/E ratios was constrained to be no greater than the reduction required. The constrained cost-effectiveness ratios $CCER_{iL}$ were calculated as:

$$CCER_{iL} = \frac{\Delta BACT_{iL}^{IY}}{\Delta \hat{\chi}_{iL}^{IY}} \tag{4.3.6}$$

where

$$\Delta \hat{\chi}_{iL} = MIN(\Delta \chi_{iL}^{IY}, \Delta \chi_r') \tag{4.3.7}$$

Table 4.1 Constrained Cost-Effectiveness Ratios

Option	BTAC	Concentration Reduction	C/E Ratio		Option Chosen	
			Unconstrained	Constrained	Unconstrained	Constrained
1	B	R	(B/R)	(B/R)		X
2	1.5B	2R	.75(B/R)	1.5(B/R)	X	

With this definition of the constrained C/E ratio, the cheaper option 1 would be chosen for implementation in cases similar to that illustrated in Table 4.1. In Eq. 4.3.7, $\Delta X_r'$ is the concentration reduction required for attainment on the current iteration, that is after the initial ΔX_r corresponding to the binding year (Eq. 3.2.15) has been reduced to account for options previously implemented by the strategy. It is worth emphasizing that $\Delta X_r'$ is a quantity appropriate to the binding year which may be the MY and should thus be calculated differently than the quantities appropriate to the IY. This difference is taken into account when $\Delta X_r'$ is updated. The option chosen for implementation on a particular iteration is the one associated with the particular source I with the lowest constrained cost-effectiveness ratio, $CCER_{IL}$.* The procedures outlined above for choosing the option to be implemented corresponds to boxes 7-10 in Fig. 4.2.

4.3.2 Calculation of Impact

After a specific option P_{IL} had been chosen as just described, it had to be implemented and its effect on reducing the required concentration reduction calculated. After implementation, the option P_{IL} was removed from the list of options available for implementation on the next iteration. The concentration reduction calculated in Eq. 4.3.4 is not appropriate for reducing the remaining required reduction $\Delta X_r'$, because $\Delta X_r'$ is a quantity calculated in the BY (see Eq. 3.2.15). In the BY, the effect of implementing P_{IL} is

$$\Delta X_{IL}^{BY} = T_I^L \, \Delta Q_{IL}^{BY} = T_L^I \, \Delta Q_I^o(P_{IL}) \, \phi_I^{BY} . \qquad (4.3.8)$$

The difference between ΔX_{IL}^{IY} and ΔX_{IL}^{BY} lies in the difference between the factors ϕ_I^{IY} and ϕ_I^{BY}, the difference in the fractions of sources not controlled to new source levels in the two years. If the binding year is later than the implementation year, this procedure implies than some sources controlled in the IY will wear out and be replaced by new sources emitting at new source levels by the BY even when new-source controls are less efficient than the strategy-level controls. Thus, emissions could increase over time even in the absence of new source growth. Such a situation would occur only if the strategy-level controls on replaced sources were replaced by new-source level

*Although not implemented in the earlier model, Ref. 14 indicates that use of the constrained C/E ratios may be desirable on theoretical grounds.

controls when the source itself was replaced. A more realistic simulation might assume that a source once controlled by the strategy would continue to employ strategy-level controls even when the actual emitting unit wore out and needed to be replaced. Such a dynamic approach to the selection of controls was not possible given the structure of the earlier codes. The approach adopted here maintains some independence between new-source and strategy-level controls but does lead to some unanticipated nonattainment.

Using Eq. 4.3.8, the required concentration reduction after the implementation of the option P_{IL} is easily calculated as:

$$\Delta\chi_r^{\prime}(\text{Next iteration}) = \Delta\chi_r^{\prime}(\text{Current iteration}) - \Delta\chi_{IL}^{BY}. \qquad (4.3.9)$$

This iterative procedure was continued until either

$$\Delta\chi_r(\text{Next}) < 1$$

or all available options had been implemented. Concentrations within 1 $\mu g/m^3$ of the standard were considered as attainment concentrations just as was done in determining the initial nonattainment status of each area. If all available options had been implemented and $\Delta\chi_r^{\prime}$ was still 1 $\mu g/m^3$ or more, the area was in residual nonattainment even after implementation of the control strategy.

4.3.3 Discussion

Multiple-Area Counties. In counties with more than one nonattainment area, the strategy was developed one area at a time. The assumption in the rollback model is that each source affects all receptors in a county in equal proportions. This can be seen from Eq. 3.2.7 where the source-specific factor in w_j is the same for all receptors i, the base-year air quality at different receptors determining only an overall scaling factor which is the same for all sources. After a strategy had been developed in one nonattainment area within a given county, the total concentration reduction for the next area was updated to account for nonroad options implemented in all previously considered initial nonattainment areas in that county. The coupling coefficients were those appropriate to this next area and its associated binding averaging time. The base-year emission reductions for options

already applied and the ϕ_I^{BY} factors for the BY associated with this next area were used with these coupling coefficients in Eq. 4.3.8 and 4.3.9 to determine the beginning $\Delta X_r'$ for the next area. If $\Delta X_r'$ was 1 $\mu g/m^3$ or more, the strategy selection procedure was implemented; if not, the options already applied in previous areas were sufficient to have produced attainment in the next area. As noted previously, municipal paved roads were an exception to this procedure; each nonattainment area within a county was assumed to have associated with it a separate effective fraction α of the paved roads in the county. In a county with N initial nonattainment areas, a fraction of the paved municipal roads as large as α N could have been selected for control.

Approach to the Least-Cost Solution. The procedure outlined in this section was originally developed to approximate a least-cost strategy.[2,14] It was, however, recognized that the procedure was only an approximation to a linear programming approach that would have found a true least-cost strategy. For example, all remaining options were never considered available for implementation on a given iteration, only the single remaining option with the lowest cost from each source was considered available. Cases were found where, for particular nonattainment areas, a lower cost solution could easily be generated by inspection. Since a complete linear programming approach was never applied to the attainment problem, it is not known how greatly the model deviates from a true least-cost solution at various levels of aggregation. For all counties in residual nonattainment, the method of determining a solution would be irrelevant, since all options would be applied regardless of the method used.

5 REPORTS

Several types of information were required for the development of the RIA for particulate standards:

- Cost information,
- Environmental impacts, and
- Support for other analyses
  - Economic analysis
  - Benefits analysis.

Section 5.1 deals with the first two areas; Sec. 5.2 with both aspects of the third.

5.1 COST AND ENVIRONMENTAL REPORTS

This section describes procedures represented by box 15 in Fig. 1.1 and carried out for the most part by LEASTCOST and the REPORT WRITER in Fig. 1.2C.

Costs. The costs data represented the direct costs to industry at the county, state, regional, sectional, and national levels. Several costs were of interest:

- Capital costs,
- Operating and maintenance (O&M) costs,
- Before-tax annualized costs (BTAC),
- After-tax annualized costs (ATAC)
- Single-cycle net present value (NPV), and
- Infinite-cycle net present value (ICNPV).

All of these costs could be calculated for each implemented option from the capital and O&M costs for that option. Operationally, these capital and O&M costs were saved in the solution file (file 9.1 in Fig. 1.2B) for use by the REPORT WRITER. The cost data included the factor ϕ_i^{IY} and were thus appropriate to the fraction of capacity assumed controllable during strategy development, not the entire capacity in the IY. The ϕ's, through the growth and replacement parameters, K, L, and M, varied with SIC and state. At all levels of aggregation, costs were reported at the four-digit SIC level. A

nonstandard SIC (9998) was used to identify emissions from paved municipal roads. In addition, within each SIC, the nonstandard SCC's could be used to identify nontraditional fugitive sources. For each SIC both the total cost and the cost of controlling NTF sources was reported. The NPV and BTAC costs are included in Table A.4 in Appendix A. Table A.5 provides a breakdown of the NPV costs by source category. Costs by SIC for major categories and municipal paved roads are given in Tables A.6 and A.7 for TSP and PM10, respectively.

Equations 4.2.2 and 4.2.3 show how ATAC and BTAC were calculated using the capital (C) and O&M (M) costs passed forward by the strategy. In report preparation, these costs, C and M, would differ from those used during the calculation of annualized costs in the strategy model by the inclusion of the factor ϕ^{IY}_{i}. The calculation of net present values proceeded as follows:

$$\left.\begin{aligned} NPV' &= \left\{ C + \left[\frac{(1+R)^N - 1}{R(1-R)^N} \right] \cdot M \right\} \cdot \phi^{IY} \\ ICNPV' &= \frac{BTAC}{R} \cdot \phi^{IY} = \left\{ C \left[\frac{(1+R)^N}{(1+R)^N - 1} \right] + \frac{M}{R} \right\} \cdot \phi^{IY} \end{aligned}\right\} \quad (5.1.1)$$

$$\left.\begin{aligned} NPV &= NPV' \left[\frac{1}{(1+R)^{IY-1982}} \right] \\ ICNPV &= ICNPV' \left[\frac{1}{(1+R)^{IY-1982}} \right] \end{aligned}\right\} \quad (5.1.2)$$

where all symbols have the same meanings and values as in Sec. 4. Although not shown explicitly in Eqs. 5.1.1 and 5.1.2, the calculations were carried out one option at a time with values of the variables appropriate to the option and source being considered. Since the parameters for calculating costs were appropriate to 1980, NPV's were reported as 1982 NPV's in 1980 dollars.

The regional reports corresponded to the ten EPA administrative regions. The seven sections were defined in term of sets of states representative of, for example, the Northwest or Mountain states. Appendix B

lists the states in each Region and Section. The programs could develop reports based on any desired collection of states. The national reports included all 50 states. NPV costs at the Regional and Sectional levels are given by Tables A.8 and A.9 in Appendix A, respectively.

Environmental. Environmental parameters of interest were

- Energy consumed,
- Solid waste generated, and
- Emissions reduction achieved.

The energy consumption was based on electricity used and was actually estimated by CONCOST using equations like Eq. 2.3.1 with appropriate parameters from the inventory and file 7.2 in Fig. 1.2B. For each option these energy consumption figures were adjusted by the appropriate ϕ_i^{IY} prior to reporting. Reporting was done with the same breakdowns as described above for the cost data.

Solid waste was taken as the amount of TSP collected by the options implemented and was reported on the same basis as costs. The factor ϕ_i^{IY} was included in the solid waste figures to account for the fact that only a portion of the sources were controllable by the strategy. Emissions reductions from municipal roads and nontraditional fugitive emissions were not included in the solid waste because most of the controls applied to them do not generate material that must be disposed of. For PM10 scenarios, the solid waste was still taken as the total additional TSP collected, because the control devices would still collect the TSP fraction even when installed to meet a PM10 standard.

Emission reductions in tons/yr of both TSP and PM10 were calculated for all scenarios and reported on the same basis as costs. As with the previous quantities, the factor ϕ_i^{IY} was included to retain consistency between all cost and environmental figures and the fraction of sources actually controlled by the strategy. Information on emission reductions achieved is provided in Tables A.5-A.7 in Appendix A.

In addition, a final status report on the final air quality in each initial nonattainment county was available from LEASTCOST (file 13.1 in Fig. 1.2B). The final status report gave the final stutus (MET, NOT MET) of each initial nonattainment area. Areas all of whose sources had data deficiencies precluding development of control options were also indicated. The difference

between the concentration achieved by the strategy and the binding standard was reported for each area and the national nonattainment status was summarized in terms of the number of areas in attainment and in residual nonattainment in the binding year. In Appendix A, Tables A.4, A.8, and A.9 summarize the initial and final nonattainment status at the National, Regional, and Sectional levels, respectively.

5.2 SUPPORT FOR OTHER ANALYSES

Separate economic and benefit analyses were undertaken by other workers. These analyses both used some of the information developed by this work and both required additional processing to provide new data.

Economic Analysis. Reports (box 9.0 on Fig. 1.2B) giving, among other outputs, the capital, O&M, ATAC, BTAC, and NPV costs broken down as described above were supplied to the contractor (EEA) doing the economic analysis. In addition, the information on final attainment status (file 13.1 on Fig. 1.2B) was also supplied. Based on an analysis of this data, the contractor requested plant-specific information for a list of SIC's that appeared to sustain large economic impacts. To provide this information, the program LESCO in Fig. 1.2C was developed. At the plant level the intention was to look at a "worst-plant" case. Since it would be possible that no replacement or growth at a particular plant would have been required to apply new source controls prior to implementation of the control strategy, EEA wanted the plant-specific costs calculated assuming that all growth and replacement would be subject to control by the strategy. By matching the option-by-option information in the solution file 9.1 in Fig. 1.2B, which specified both the source and the SIC, with the associated plant in the directory (file 12.1 in Fig. 1.2A), the required information was developed for the plant files (file 12.0 in Fig. 1.2C) Plant-specific cost information could be provided both with all sources controlled by the strategy and with only that fraction represented by the factors ϕ_i^{IY} controlled by the strategy. The former costs will generally exceed the later but will be different from the costs included in the national totals produced by this work. In any plant, even in the worst-plant case, only those sources actually picked by the strategy model were assumed to incur costs.

Benefits Analysis. The benefits analysis was performed by Mathtech. Ideally, air quality information before and after the application of the control strategy would have been available on a yearly basis over about a 15 year period to support this analysis. Such data would have permitted the calculation of yearly absolute and incremental concentrations as inputs to various benefit functions. In addition, the nature of the benefits functions required concentration estimates for both annual and 24-hour averaging times even for scenarios which specified only a single averaging time. The earlier static model had been extended for this work to provide estimates for four years beyond the base year: 1985, 87, 89, and 95. Because projections were not made for all years and all averaging times for each scenario, new programs were developed to provide the desired information. The program PROJAQ (Fig. 1.2C) projected concentrations of TSP and PM10 for annual and 24-hour averaging times for the four years in the absence of a control strategy. To retain consistency with the pre-strategy projections used to determine the binding conditions and the required concentration reductions, these projections were made on the basis of county-wide emissions by using Eq. 3.2.11, the case equivalent to coupling coefficients with $w_j = 1$. Concentrations after the application of the control strategy were projected by the program NEWAQ (Fig. 1.2C). These projections were made by in a manner consistent with the manner in which concentrations were handled during strategy development. Weighted coupling coefficients were used and the concentration reduction associated with each implemented option was calculated as in Eqs. 4.3.3 and 4.3.4 with the year of interest rather than the IY being used in the calculations. The calculations were, of course, extended to both pollutants and averaging times. After the total reduction had been calculated, the after-strategy concentration could be found by substraction. Operationally, many of the basic calculations were actually made by earlier programs in the sequence and have been summarized here for convenience.

6 ADDITIONAL ANALYSES

In addition to the base analysis described above, several additional analyses were conducted to address related issues. At EPA's request, an attempt was made to estimate the cost associated with the reduction of residual nonattainment as described in Sec. 6.1. Other analyses described in Sec. 6.2 looked at the sensitivity of the results to various system parameters and investigated several areas bearing upon the validity of the results.

6.1 REDUCTION OF RESIDUAL NONATTAINMENT

In some areas, the strategy did not result in attainment of the binding standard in the binding year. The costs required to bring most of these residual nonattainment areas into attainment were estimated as follows by a program not shown on Fig. 1.2. Some results of estimating the costs for the reduction of residual nonattainment by the procedures discussed below are given in Tables A.4 and A.10 in Appendix A.

The data available included:

$$\Delta X_i^o = X_i^o - X_i^{STD} \tag{6.1.1}$$

where X_i^o is the initial projected concentration corresponding to the binding standard X_i^{STD} in the binding year. ΔX_i^o was thus the initial exceedance of the binding standard and was available for each area in the violations file (file 8.2 in Fig. 1.2B). As noted in the last section, the nonattainment status file (file 13.1 in Fig. 1.2B) contained the value of ΔX_i^F, the difference between the concentration after application of the strategy and the binding standard:

$$\Delta X_i^F = X_i^F - X_i^{STD} \tag{6.1.2}$$

where X_i^F is the projected concentration after application of the strategy. The total concentration reduction achieved in a particular area is

$$X_i^o - X_i^F = \Delta X_i^o - \Delta X_i^F. \tag{6.1.3}$$

Had area-level costs C_i been available, the average cost per unit air quality improvement T_i could have been obtained from:

$$T_i = \frac{C_i}{\Delta X_i^o - \Delta X_i^F}. \tag{6.1.4}$$

An estimate of the additional costs required to reach attainment in that area might then have been obtained from

$$\Delta C_i = T_i \times \text{MAX}(0, \Delta X_i^F - 1). \tag{6.1.5}$$

The second factor is zero if $\Delta X_i^F \leq 1$, that is, if the area is already in attainment as defined in other phases of this work. In these areas, no additional costs would be incurred. Equation 6.1.5 assumes that the costs in terms of dollars per unit air quality improvement are the same for sources picked by the strategy and for sources not picked by the strategy and/or not in the inventory. Since many small sources were eliminated from the inventory in initial screening, only larger sources remained to be controlled and, to the extent that small sources give a different air quality improvement per dollar than do large sources, Eq. 6.1.5 is not strictly true. If sources similar to those picked by the strategy were really present in the area but were not in the inventory, the equation is reasonable, but in such areas, the very absence of these sources would cast doubt upon the accuracy of the base inventory. As will be seen later (Sec. 6.2), sources were eliminated from the strategy by the cost-effectiveness caps. It may be reasonable to assume that these sources would have been cost-ineffective in terms of their concentration reductions as well as in terms of their emission reductions. Based upon such an assumption and the further assumption that the high cost-effectiveness ratios found in this work did not always result from incorrect data in the inventory, the results of the analysis itself indicate that costs per unit air quality improvement may go up substantially for concentration reductions beyond those already found by the strategy.

With these caveats in mind, the total cost C_i^{TOT} in area i for the strategy as developed and for the reduction of residual nonattainment would be

$$C_i^{TOT} = C_i + \Delta C_i = \mu_i C_i \tag{6.1.6}$$

where

$$\mu_i = 1 + \left(\frac{\text{MAX}(0, \Delta X_i^F - 1)}{\Delta X_i^o - \Delta X_i^F} \right) = \frac{\Delta X_i^o - \text{MIN}(1, \Delta X_i^F)}{\Delta X_i^o - \Delta X_i^F}$$

$$= \begin{cases} 1 + \left(\dfrac{\chi^F - \left(\chi_i^{STD} + 1 \right)}{\chi_o - \chi^F} \right), & \text{in residual nonattainment areas} \\ 1, & \text{in attainment areas.} \end{cases} \qquad (6.1.7)$$

As Eq. 6.1.7 shows, μ_i has a value of one in an attainment area, that is, no increase in costs would be associated with an attainment area. In a nonattainment area, the second term in Eq. 6.1.7 corresponds to the costs associated with the reduction of residual nonattainment. The numerator of this term is the air quality improvement required to go from the air quality attained by the strategy to 1 $\mu g/m^3$ above the standard (attainment). The denominator is the air quality improvement already achieved by the strategy. Thus, costs are increased by the ratio of the air quality improvement required for attainment to the air quality improvement already achieved by the strategy. The multiplier μ_i would not be calculated for an area in which missing source data precluded the implementation of any options. These areas correspond to those having $\Delta\chi_i^o = \Delta\chi_i^F$. County level costs were not readily available; the county-level REPORT WRITER could handle only one county at a time and would have had to have been run hundreds of times for a typical scenario to produce such data. However, the multiplier μ_i could be evaluated for each area. The approach taken here was to calculate two national estimates of μ, one an average and the other a median:

$$\bar{\mu} = \frac{1}{N'} \sum_{i=1}^{N'} \mu_i$$

and (6.1.8)

$$\mu_M = \text{MEDIAN}(\mu_1, \mu_2, \ldots, \mu_{N'})$$

where N' is the number of residual nonattainment areas with certain "intractable" areas left out.

In developing this approach, it was found that some areas had multipliers larger than 500. A single such area could have a significant impact on average $\bar{\mu}$ and, in fact, could almost completely determine the value of $\bar{\mu}$. These counties were generally, but not always, associated with large emissions from unpaved municipal roads and other area sources not considered as condidates for control during strategy development. Since most of the emissions could not be controlled, the strategy could make little progress toward

attainment and if any substantial initial nonattainment existed, the associated multipliers (μ_i) tended to be very large. In such "intractable" areas, the types of controls being considered by the strategy were inappropriate to the problem. Intractable areas, more than 75% of whose emissions of the pollutant of interest were found to come from sources not subject to control in the base year, were eliminated from consideration in calculating $\bar{\mu}$ and μ_M. It should be noted that even with this definition, these were cases where intractable counties came into attainment when the strategy was applied. After intractable areas were eliminated, some areas still had large multipliers. Areas with $\mu_i > 100$ were also eliminated from consideration in calculating $\bar{\mu}$ and μ_M, since they were believed to be indicative of possible problems with the data bases if they did not correspond to intracable areas.

Having the multipliers given by Eq. 6.1.8, new national totals were calculated from

$$\left.\begin{aligned} C_{AVG}^{TOT} &= \bar{\mu} \times C \\ C_{MED}^{TOT} &= \mu_m \times C \end{aligned}\right\} \qquad (6.1.9)$$

where C is the national cost calculated for all N initial nonattainment areas ($N' \leq N$) by the strategy model:

$$C = \sum_{i=1}^{N} C_i \qquad (6.1.10)$$

6.2 SENSITIVITY ANALYSES AND POTENTIAL PROBLEMS

A number of sensitivity analysis were conducted to look at the effect of various parameters whose values were particularly uncertain. In addition, a retrospective look was taken at four areas which were considered to be particularly prone to problems either in the earlier model or in this work.

6.2.1 Sensitivity Analyses

These analyses were conducted by sequencing through the main programs beginning with GROWTH or a later appropriate starting point and ending with the REPORT WRITER using appropriately chosen values of the parameter(s) of interest or with switches set to control the processing appropriately.

Growth Parameters. Table 6.1 summarizes the results obtained by varying the growth parameters a and b for point sources and α, β, and γ, for area sources (see Eqs. 3.1.12 and 3.1.22). All runs were made for the PM10(70,250)/89 scenario with PM10 standards of 250 $\mu g/m^3$ expected 24-hour value and 70 $\mu g/m^3$ arithmetic annual mean with an IY of 1989 and the standard MY of 1995. As might be expected, the results were quite sensitive to the choice of growth parameters. The first three lines in the table show the effect of increasing the fraction b of replacement sources coming on at current rather than at equally or more efficient new-source control levels. A larger value of b corresponds to larger projected emissions and as expected the number of nonattainment areas and the national costs increase with b. Results for a, the fraction of new growth sources coming on at base control levels are not presented here. A behavior similar to the behavior with b was exhibited in early runs when certain minor errors were still present in some codes. After correction, the analysis for b was rerun without showing appreciable changes at the national level. Given the results for b and the anticipated deadlines, the analysis for a was not redone. The last two lines in Table 6.1 show the effect of increasing the effective fractions for paved roads and area sources. To accentuate the effect, all area sources have been allowed to grow at the population growth rates (γ = 1), not just the paved road emissions as under the base conditions (γ = 0). Nonattainment and costs increase as the effective area source fractions increase. Costs will all area

Table 6.1 Effect of Growth Parameters[a]

Points		Areas			Number of Nonattainment Areas		National NPV Costs (10^6 $)
a	b	α	β	γ	Initial	Residual	
0	0	0.01	0.01	0	72	37	403
0	0.5	0.01	0.01	0[b]	105	50	757
0	1.0	0.01	0.01	0	144	68	1,150
0	0.5	0.1	0.1	1.0	124	63	952
0	0.5	1.0	1.0	1.0	134	81	3,004

[a]Run for the standard PM10(70,250)/89.

[b]Parameters used in base analysis runs.

sources effective are quite large compared to the costs in other cases. In this case ($\alpha = \beta = \gamma = 1.0$), the other area sources are all effective and all grow. These are the sources that are not potentially controllable by the strategy and point sources must be controlled to offset the emissions from these sources and costs rise significantly. This situation is another manifestation of the underlying cause of the intractable areas discussed in Sec. 6.1. These results clearly indicate that the choice of the growth parameters has an important effect on the final nonattainment status and the final costs. The base set chosen here was felt to represent a reasonable choice based on available information but the reasons for the particular choices are by no means completely persuasive.

Diesels. As estimates for diesel contributions were not available until the base analysis was well underway, they were not included in the base analysis runs. Table 6.2 summarizes the effect of including the diesel contributions as a time-dependent additive contribution to background as well as the results of some other sensitivity analyses. Comparison of the results for the base analysis (item 1 in Table 6.2) and the results with diesels included (item 2) indicates that inclusion of the uncontrollable diesel contributions increases both the number of nonattainment areas and the national costs again because point sources must be controlled to offset the uncontrollable diesel emissions. The diesel contributions could change both the binding year and the binding averaging time from those chosen without considering diesels. Based on the limited data in the table, the effect appears larger for PM10 than TSP as might be expected, since all diesel emissions are PM10. The diesels have an impact that would be best taken into account but that would probably not be large enough to affect the validity of comparisons between alternative standards based on scenarios without diesel emissions.

Generic New-Source Efficiencies. In the base analysis, new-source controls were assumed to be 98% efficient for SIC 33 and 99% efficient for all other SIC's unless inventioned efficiencies were greater. As discussed previously, the projection procedures could in essence replace efficient controls applied by the strategy with less efficient new-source controls in making projections beyond the implementation year. Item 3 in Table 6.2 shows the results of a PM10 run made with a generic new-source efficiency of 99.7%

Table 6.2 Sensitivity Analyses[a]

Item	Scenario	Parameters: Diesels Included?	Generic New Source Efficiency(%)	C/E Caps	Maintenance Required	Population Growth Rates	Number of Nonattainment Areas: Initial	Number of Nonattainment Areas: Residual	National NPV Costs (10^6 $)
1[b]	PM10(70,250)/89	N	99/98[c]	Y	Y	Base	105	50	757
	TSP(75,150)/87	N	99/98	Y	Y	Base	541	308	3,352
2	PM10(70,250)/89	Y	99/98	Y	Y	Base	113	55	815
	TSP(75,150)/87	Y	99/98	Y	Y	Base	554	317	3,437
3	PM10(70,250)/89	N	99.7/99.7	Y	Y	Base	82	34	474
4	PM10(70,250)/89	N	99/98	N	Y	Base	105	99	32,470
5	PM10(70,250)/89	N	99/98	Y	N	Base	90	33	638
6	PM10(70,250)/89	N	99/98	Y	Y	Mathtech	105	50	757

[a]All runs made with base growth parameters ($a = 0$, $b = 0.5$, $\alpha = .01$, $\beta = .01$, $\gamma = 0$).

[b]Base analysis conditions.

[c]99/98: 98% for SIC 33, 99% for all other SIC's.

for TSP, the highest TSP efficiency among the options available to the strategy. Increasing the new-source efficiency should reduce projected emissions and thus nonattainment and costs in comparison to the base conditions. Substantial reductions in both parameters are shown in the table indicating that the choice of an appropriate generic value for new-source controls was an important consideration in developing the model. Although not subjected to comparison with the BACT clearing-house information as was reportedly done in making the 99/98% generic estimates used here (see Ref. 2), earlier estimates of SCC-specific controls and efficiencies are available and have been reviewed by both EPA and industry groups (see, for example, Ref. 15). Such estimates should be considered in future work given the large effect apparently associated with the choice of new-source levels.

Cost-Effectiveness Caps. Item 4 in Table 6.2 illustrates the effect of removing the cost-effectiveness caps. In this run, all options were considered available regardless of their cost-effectiveness in terms of dollars per ton of emissions reduced. National costs increase by over a factor of forty while only one additional area comes into attainment. Even though different values for the caps were not used, it is clear that the values chosen do keep the national costs at a reasonable level. Presumably, options screened out by the C/E caps include those for which bad data caused very high costs to be calculated and those for which the costs would really be prohibitive. As noted in Sec. 6.1, the existence of valid, very expensive options would seriously weaken the assumptions made in estimating the costs for the reduction of residual nonattainment.

Maintenance Requirement. The requirement that the standards be maintained until 1995 was switched off for the results given in item 5 in Table 6.2. In the base runs, both the implementation year and the maintenance year were examined for nonattainment. With maintenance not required, only the implementation year was examined as was the case in the earlier model.[2] With maintenance required, one would expect to find more nonattainment and additional costs being required to offset the additional growth beyond the implementation year. The results support this expectation. Choice of other maintenance years would have changed the magnitude of the effect, but it is clear that if maintenance is likely to be required beyond 2-3 years, then the requirement must be explicitly included in the development of the air quality

and cost models. Neglect of the maintenance of ambient standards would lead to serious underestimates of nonattainment and costs.

Population Growth Rates. The population growth rates used by Mathtech in the analysis of benefits differed from those used in this work to project emissions from area sources. As item 6 in Table 6.2 shows, the effect of using Mathtech's population growth rates was negligible. Since the Mathtech rates were neither uniformly higher nor uniformly lower than the base rates used here and since only one percent of municipal paved roads were assumed to be effective and to grow under base analysis conditions, the indicated insensitivity is not surprising.

Wind Speed. As noted when the weighted coupling coefficients were discussed in Sec. 4.1, the choice of 2.5 m/sec for the wind speed used in calculating the plume rise in the earlier model was low considering the range of wind speeds consistent with C stability. (In regard to the use of any single wind speed and the appropriate choice of a weighting factor dependent on stack height, the reader should consult the subsection on Weights for Coupling Coefficients later in Sec. 6.2.2.) To test this assumption, several runs were made with an intermediate version of the model with an approximate

Table 6.3 Effect of Wind Speed[a]

Scenario	Wind Speed (m/sec)	Number of Nonattainment Areas	
		Initial	Residual
PM10(55,150)/89	2.5	332	156
	4.4	332	155
PM10(55,150)/95	2.5	409	233
	4.4	409	231
PM10(85,225)/89	2.5	116	51
	4.4	116	50

[a]These results were produced by an intermediate version of the model and are not directly comparable to the base results presented elsewhere in this document.

"national average" wind speed of 4.4 m/sec.[16] The results are presented in Table 6.3. Cost data were not computed for these runs. Some corrections were made to the model between the time when the wind speed analysis was done and the final base runs were made. Thus, the results in the table are not perfect indicators of what would happen with the final, updated system. However, since the changes in the model affected the status and costs of only a small number of areas, it was considered safe to conclude that the results are fairly insensitive to wind speed as shown in the table. The higher wind speed should reduce the plume use and hence increase the relative contributions of the large, hot stack sources with respect to the nontraditional fugitive sources with effective release heights of 10 m ($w_j = 1$). In a small number of areas, this effect apparently leads to a slight improvement in the nonattainment picture. This difference should be considered insignificant when compared to the errors associated with the rollback approach itself.

6.2.2 Potential Problems

The methods applied in several areas were investigated as being sources of potential problems. As will be seen the effects of the methods actually used were perceptible but with one exception were considered to be well within the accuracy expected of the area-level rollback approach adopted for this work.

Unanticipated Nonattainment. As already discussed in Sec. 3.2.3 the selection of the binding conditions and the development of an attainment strategy corresponding to them does not guarantee attainment in nonbinding years because emission reductions sufficient to reach attainment may not be available in these years. In addition, attainment could not be guaranteed in a year or for an averaging time not considered when the binding conditions were chosen. The program FQCHKS (Fig.1.2C) was developed to look for such unanticipated nonattainment. This program compared the air quality projections for 1985, 87, 89, and 95 with the applicable standards. The results for various standards are summarized in Table 6.4. Violations prior to the year were not counted as unanticipated violations. Detailed inspection of the results showed that among the two years considered in choosing the binding conditions, unanticipated violations could occur in the year considered but not chosen as the binding year as well as in a year between the two years.

Table 6.4 Unanticipated Nonattainment

Scenario	Number of Nonattainment Areas	
	Base Residual[a]	Unanticipated[b]
TSP(75,-)/87	139	5
TSP(-,150)/87	304	5
TSP(-,260)/87	73	4
TSP(75,260)/87	150	5
TSP(75,150)/87	308	5
PM10(55,-)/89	88	2
PM10(70,-)/89	41	0
PM10(90,-)/89	11	0
PM10(-,150)/89	158	2
PM10(-,200)/89	71	1
PM10(-,250)/89	32	0
PM10(-,300)/89	18	0
PM10(55,150)/89	165	2
PM10(55,250)/89	92	3
PM10(70,200)/89	78	1
PM10(70,250)/89	50	0
PM10(90,300)/89	19	0

[a]Base analysis for binding conditions only.

[b]Number of areas in attainment under the binding conditions with one or more violations of an applicable standard beyond the binding year.

Unanticipated violations were also found for the nonbinding averaging time in a nonbinding year.

The number of unanticipated nonattainment areas is always small in comparison to the total number of nonattainment areas and should not seriously affect the results. Rough calculations of the costs needed to eliminate the unanticipated nonattainment showed additional costs, which, although not negligible, were well within the expected errors of the base cost estimates.

There are several expected causes for the unanticipated nonattainment. First, the coupling coefficients used in projecting emissions and those used in developing the strategy are inconsistent, the first set having equal

weights and the second set being weighted by the effective release height factors. Whether this inconsistency, as built into the earlier model,[2] contributes to unanticipated nonattainment has not been investigated in detail, but giving a source one impact when air quality is projected and the binding conditions are chosen and a different impact when the strategy is developed should be avoided if possible. If it were desired to use weighted coupling coefficients, an improved system would first determine the coupling coefficients as in ROLLBACK, proceed to use these coefficients to project air quality in MARGIN, and finally use the same coefficients in CONCOST and LEASTCOST to develop the strategy.

Second, it is clear that the choice of the binding conditions is simply not appropriate to the situation being simulated. The method fails because replacement may result in sufficient emission reductions not being available from sources controlled for the binding conditions to guarantee attainment for other years and averaging times. If it is desired to use a shortened procedure rather than a dynamic one of making projections year by year with ongoing updates of each source's control status, the margins must include some consideration of the weighted concentration reductions available in each projection year, not just a simple consideration of the projected air quality relative to the standard. Scheduling and the structure of the original programs precluded implementation of more than a simple extension of the earlier margin concept in this work. However, as Table 6.4 shows that this simple extension was quite good considering the overall errors associated with this type of analysis.

Weights for Coupling Coefficients. As noted in Sec. 4.1, more defensible weighting factors than those developed for the earlier model and used in this work can be derived for the coupling coefficients. Because the effects of using these different weighting factors may be substantial, it is unfortunate that scheduling precluded the development and inclusion of the following alternative approach in the models used for this work. According to Refs. 16 and 17, the maximum ground-level concentration, $\chi_m(u)$, for unstable and neutral conditions can be given by

$$\frac{\chi_m(u)}{Q} = B \cdot \frac{u^{b/d}}{(uh + C)^{(1 + b/d)}} \cdot \qquad (6.2.1)$$

The derivation of Eq. 6.2.1 assumes

- The familiar Gaussian-plume model,
- The commonly used representations of the horizontal and vertical dispersion coefficients given by

$$\left.\begin{aligned}\sigma_y(x) &= ax^b \\ \sigma_z(x) &= cx^d\end{aligned}\right\} \qquad (6.2.2)$$

  where x = downwind distance

- The Briggs' neutral/unstable plume rise formula.

In Eq. 6.2.1

Q = emissions rate,

u = wind speed,

h = physical stack height,

B = a factor which depends on b,d, and a but is a constant for a given stability class and is independent of wind speed u within a given stability class, and

$$C = \begin{cases} 21\ F^{3/4}\ m^2/sec \text{ for } F < 55\ m^4/sec^3 \\ 39\ F^{3/5}\ m^2/sec \text{ for } F > 55\ m^4/sec^3 \end{cases} \qquad (6.2.3)$$

where

$$F = g\left(\frac{T - T_a}{T}\right) V \qquad (6.2.4)$$

and

g = the acceleration due to gravity,

T = exit gas temperature (°K),

T_a = ambient atmospheric temperature (°K), and

V = exit gas flow rate at temperature T (m^3/sec).

In the Briggs formulation, the plume rise Δh is given by

$$\Delta h = \frac{C}{u} \cdot \qquad (6.2.5)$$

Units have not been specified for all quantities listed above because they are not necessary to understand the argument. Details on the derivation of Eq. 6.2.1 may be found in either of the references. The salient points to be noticed in the above summary are 1) that for cold sources like nontraditional

fugitives and municipal roads with $T = T_a$, the factor C, being proportional to $T - T_a$, is zero and 2) that all dependence on windspeed and physical stack height h is given explicitly by Eq. 6.2.1. From this equation it can be shown that a windspeed defined by

$$u_w = \frac{b}{d} \cdot \frac{C}{h} \tag{6.2.6}$$

results in the largest of the maximum concentrations, w:

$$\frac{\chi_w}{Q} = B \cdot \frac{1}{Ch^{b/d}} \cdot \frac{(b/d)^{b/d}}{(1 + b/d)^{(1+b/d)}} , \quad C \neq 0. \tag{6.2.7}$$

Equation 6.2.7 is only true for stacks with $C > 0$. For two such stacks 1 and 2 the ratio of the worst concentrations for per unit emission rates is

$$\frac{\chi w_1}{\chi w_2} = \frac{C_2 h_2^{b/d}}{C_1 h_1^{b/d}} . \tag{6.2.8}$$

For the case of C stability assumed in the earlier model, b/d is close to one. Taking b/d = 1 as is done in the ISC model for C stability[17] gives

$$\frac{\chi w_1}{\chi w_2} = \frac{C_2 h_2}{C_1 h_1} . \tag{6.2.9}$$

suggesting that a weighting factor $(10/C_j h_j)$ where h_j is the physical stack height would have been more appropriate than the weighting factor $(10/H_j)$ where H_j is the effective stack height as implemented in the earlier model.[2] The value of C_j could have been determined, since the model uses Briggs' equations to determine H_j. Reference 17 has an equation similar to Eq. 6.2.8 but without the factors C_1 and C_2. Since the case being considered in Ref. 17 is that of two different heights for the same stack, $C_1 = C_2$ and Eq. 6.2.8 agreees with the reference.

For cold sources, C = 0 and Eq. 6.2.1 becomes

$$\left(\frac{\chi_m(u)}{Q}\right) = \frac{1}{u} \cdot \frac{1}{h^{(1+b/d)}} , \quad (C = 0). \tag{6.2.10}$$

In this case, the predicted maximum gets as large as desired at sufficiently low wind speeds. However, C stability requires a wind speed in excess of 2 m/sec so the worst concentration occurs with u = 2 m/sec. The ratio of the

worst concentrations for unit emissions from two stacks emitting at ambient temperature under C stability would thus be

$$\frac{X_{w_1}}{X_{w_2}} = \frac{h_2^2}{h_1^2} \cdot \qquad (6.2.11)$$

Equation 6.2.11 suggests that a weighting factor of $(10/h_j)^2$ would be more appropriate for cold sources than the factor $(10/H_j)$.

It is also worth noting that since

$$uH = u(h + \Delta h) = u(h + \frac{C}{u}) = uh + C, \qquad (6.2.12)$$

Eq. 6.2.1 can be rewritten for C stability (b/d = 1) to give:

$$\frac{X_m(u)}{Q} = \frac{B}{u} \cdot \frac{1}{H^2} \cdot \qquad (6.2.13)$$

Thus, the maximum concentration is proportional to $(1/H^2)$ for an arbitrarily chosen wind speed suggesting that a weighting factor of $(10/H)^2$ would be better than either $(10/H)$ or $(10/h)^2$ if the assumption is <u>not</u> made that the wind speed affecting each source in the area is its own source-specific critical wind speed u_w. Equation 6.2.13 does not give the highest maximum concentration but it does evade the unrealistic assumption that each source is affected by its own unique, critical wind speed. This assumption is a key concern in the formulation used in both the earlier model and this work.

In view of the above, the model was run with weighting factors $(10/H_j)^2$ to examine to effect of the change in functional form alone without the change from effective to physical stack height. Table 6.5 summarizes the results for the weighting factors $(10/H)$ and $(10/H)^2$ along with the results for w_j=1 and the recommended weighting factors. The significant impact of the value of the exponent is indicated by the table; additional areas come into attainment and total costs go down. Both the $(10/H)$ and $(10/H)^2$ formulations would predict a better final attainment picture at less cost than would have been predicted using traditional rollback (w_j=1). The use of H_j instead of h_j is, of course, at variance with Eqs. 6.2.9 and 6.2.11. However, the results in the table would apply to a set of fictitious sources with physical stack heights equal to the effective stack heights actually used. Although the range of stack heights associated with these fictitious sources is larger than the range of physical stack heights in the inventory, the results show that the choice of the weighting factor is an area of some concern. It should

Table 6.5 Weighting Factors for Coupling Coefficients

Scenario	Coupling Coefficient Weighting Factor (w_j)	Number of Nonattainment Areas		National NPV Costs (10^6 $)
		Initial	Residual	
PM10(70,250)/89	(10/H)	105	50	757
	$(10/H)^2$	105	44	577
	1	105	53	879
	Recommended	105	55	888
TSP(75,150)/87	(10/H)	541	308	3,352
	$(10/H)^2$	541	293	3,066
	1	541	316	3,910
	Recommended	541	341	3,956

also be noted that the tabulated results are based on a formulation agreeing with Eq. 6.2.13 based on maximum concentrations rather than worst case concentrations.

The following procedure should provide a more defensible approach than that inherited from the earlier model being based on Eq. 6.2.1 which can be derived by generally accepted procedures as was done in Refs. 16 and 17. Equation 6.2.1 is used because it incorporates both cases discussed above ($C = 0$ and $C \neq 0$). For consistency with the earlier model, we choose C stability and pick a minimum allowable wind speed of 2.5 m/sec, slightly above the minimum wind speed consistent with C stability. The extension to other stabilities should present no great difficulties.

The steps in the procedure for a particular source j are:

1. Choose $h_j = \text{MAX}(h_{j,\text{inv}}, 10\text{ m})$.
2. Pick an arbitrary wind speed u*, say u* = 4 m/sec. Calculate H_j using BEH072. For area and non-traditional fugitive sources, set $H_j = 10$ m.
3. Calculate $\Delta h_j = H_j - h_j$.
4. Calculate $C_j = \Delta h_j / u^*$.
5. Find the critical wind speed $u_{w,j}$ for the source from

$$u^*_{w,j} = C_j / h_j .$$

6. Choose $u_{w,j} = \text{MAX}(u^*_{w,j}, 2.5\text{ m/sec})$.
7. Calculate the weight from

$$w_j = \frac{250\, u_{w,j}}{(u_{w,j} h_j + C_j)^2} .$$

Step 1 simply assigns a minimum physical stack height of 10 m to all sources. Area and nontraditional fugitive sources inventoried without stack heights would be assigned a physical stack height of 10 m. Step 2 is the same as in the current procedure. Effective stack heights are calculated using BEH072 for stack sources. Areas and nontraditional fugitives are given effective stack heights equal to their physical stack heights. The purpose of Step 2 is to permit the estimation of C_j from Eq. 6.2.5. Alternatively, C_j could be calculated directly from Eq. 6.2.3. Since C_j is independent of wind speed the choice of u* in step 2 is arbitrary. Having the effective stack height from Step 2 and the physical stack height from Step 1, the plume rise can be found as in Step 3 and used to calculate C_j in Step 4. By construction h_j and C_j will be zero for nontraditional and area sources and perhaps for additional sources in the inventory. Given C_j, Step 5 calculates the worst case wind speed from Eq. 6.2.6 with b/d = 1 by assumption. The $u^*_{w,j}$ so calculated is zero for the "cold" sources and is assigned a reasonable minimum value of 2.5 m/sec in Step 6. Finally, the weighting factor is calculated in Step 7 which follows directly frm Eq. 6.2.1 with b/d = 1 by an argument similar to that used to derive Eqs. 6.2.9 and 6.2.11. The factor of 250 was chosen to make w_j = 1 for cold, ground-level sources (C = 0, h = 10, u_w = 2.5). As pointed out in Sec. 4.1, the coupling coefficients are only defined with a multiplicative factor so B can be dropped as long as a single stability is involved and any desired number could have been chosen in place of 250.

As a numerical example consider a stack with realistic parameters of

$h = 50$ m, and
$F = 55$ m^4/sec^3

and compare the weight assigned this stack in comparison to the weight assigned to the nontraditional sources and roads in the earlier $(1/H_j)$ system and in the $(1/H_j)^2$ system. All three systems assign a weight of one to the cold, ground-level sources. For the example stack, it can be shown that:

$C = 400$ m^2/sec.
$u_w = 8$ m/sec, and

$$w_j = \frac{1}{320} .$$

For the example, it is convenient to calculate C from Eq. 6.2.3 and u_w from Eq. 6.2.6. For the 2.5 m/sec wind speed assumed in the (10/H) and $(10/H)^2$ models, the plume rise calculated by BEH072 can be closely approximated by using Eq. 6.2.5. Thus, Δh = 160 m and H = 210 m. Then,

$$w_j' = \frac{10}{210} = \frac{1}{21} \text{ by the } (10/H_j) \text{ method}$$

and

$$w_j' = \left(\frac{10}{210}\right)^2 = \frac{1}{461} \text{ by the } (10/H_j)^2 \text{ method.}$$

Thus, relative to cold, ground-level sources, the system proposed here would assign the stack a weight between those assigned by the other two systems.

The proposed system accurately represents the relative worst-case concentrations of different sources, which representation was the unaccomplished intent of the $(10/H_j)$ system.[2] In these terms it is clear that the intent of the weighting system is somewhat absurd; it assumes that each source is located at its critical distance from the receptor of interest and is affected by a source-specific critical wind speed. This is probably the main reason why this system would lead to predictions of more residual nonattainment and higher costs than the other three systems of assigning weighting factors (see Table 6.5). Without further investigation it cannot be said whether one of these four systems is best and whether if one is, in what sense it is best. It can be said, however, that the proposed system is derived mathematically and with a clear rationale from generally accepted formulations. Whether that rationale adequately simulates the situation of interest within the context of a rollback model is another question.

Capital Costs for Plant Roads. The options file (file 6.1 in Fig. 1.2B) used in this work contained no capital costs for controlling unpaved plant roads through paving. The latest version of the documentation on that file (Ref. 3) indicates that capital costs should be associated with the option of paving plant roads and that O&M costs should also be revised. Table 6.6 summarizes the results of two runs made with these changes included. Little change is noted in the nonattainment status but national NPV costs decrease somewhat. Assuming that essentially the same options are chosen regardless of whether the base or the revised options file is used, the decrease in NPV may be due primarily to the fact that capital costs are

Table 6.6 Paving Unpaved Plant Roads

Scenario	Capital Costs for Paving Unpaved Plant Roads?	Number of Nonattainment Areas		National NPV Costs (10^6 $)
		Initial	Residual	
PM10(70,250)/89	N[a]	105	50	757
	Y	105	50	718
TSP(75,150)/87	N[a]	541	308	3,351
	Y	541	307	3,135

[a]Base analysis conditions.

discounted in computing NPV whereas O&M costs are not. With the revised options file O&M costs are reduced and replaced by capital costs which are discounted in calculating NPV. In fact, examination of the cost reports shows increased capital costs and reduced O&M costs with the revised options file. The tabulated results indicate that the errors in the costs resulting from using the original EEA options file are not negligable but are probably under 10% and are unlikely to seriously affect relative comparisons between alternative standards at the national level.

Controls for Fugitives. Examination of the options file (file 6.1 in Fig. 1.2B) indicated that chemical stabilization, a control method generally used to control emissions from roads and storage piles, had been listed as a control method for a number of industrial process fugitive sources like sand handling in foundaries. It was felt that chemical stabilization would not normally be applied to many of these sources. One run was made in which the suspect options were eliminated. No options were available in the revised options file for the affected SCC's and hence sources with these SCC's could no longer be controlled by the strategy. Chemical stabilization was retained as an option for storage piles in this run. Table 6.7 summarizes the results of this run. As the table shows, the effect on the national totals is quite small, certainly within the range of error of the overall approach. Hence, to the extent that these control technology assignments were inappropriate, comparison of results between alternatives at the national level should not be affected. This conclusion must not be construed as implying that significant

errors could not occur at less aggregated levels, particularly at the plant level, because a particular plant could contain many sources with affected SCC's.

Table 6.7 Revised Process Fugitive Controls[a]

Scenario	Capital Options	Number of Nonattainment Areas		National NPV Costs (10^6 $)
		Initial	Residual	
PM10(70,250)/89	Base	105	50	718
	CSD[b]	105	51	725

[a]Both runs reported here include capital costs and revised O&M costs for paving unpaved plant roads.

[b]CSD: Chemical stabilization deleted from control options for fugitive process sources.

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APPENDIX A: SUMMARIES OF SELECTED RESULTS

The tables in this appendix provide cost and selected environmental results for some of the scenarios investigated. A scenario is specified by an annual and/or a 24-hour standard for a single pollutant and an attainment year. In the tables, the scenarios are listed according to the following scheme:

POL (ANN, ST)/YR

where

POL = pollutant (TSP or PM10),

ANN = the value of the annual standard, if any,

ST = the value of the short-term 24-hour standard, if any, and

YR = the attainment year (1987 or 1989).

The annual standards are geometric means for TSP and arithmetic means for PM10. The 24-hour standards are second highest observed values for TSP and expected values for PM10.

Table A.1 Nationwide Emissions

Source Category	Emissions (10^6 t/yr)						
	TSP	PM10					
	1978[a]	1978[a]	1982	1985	1987	1989	1995
Point	5.04	3.67	3.53	3.47	3.44	3.43	3.50
Nontraditional Fugitive	0 43	0.23	0.26	0.29	0.31	0.33	0.42
Area[b]	0.24	0.06	0.06	0.06	0.06	0.06	0.07
Total	5.72	3.96	3.85	3.82	3.82	3.83	3.98

[a]Nominal base-year.

[b]Figures represent "effective fraction" of area source emissions. Refer to Secs. 2.2.2 and 3.1.2 for a discussion of the treatment of area sources.

Table A.2 Regional PM10 Emission Projections[a]

Year	PM10 Emissions (10^3 t/yr)										
	Region[b]										National Total
	I	II	III	IV	V	VI	VII	VIII	IX	X	
1978	82	176	577	1015	1035	334	274	163	197	103	3956
1987	74	156	537	1040	980	327	247	161	193	102	3817
1989	73	153	533	1062	977	330	244	163	194	104	3833
1995	72	146	533	1166	989	349	238	172	205	111	3981

[a]Before application of control strategy.

[b]The states in each Region are given in Appendix B.

Table A.3 Sectional PM10 Emission Projections[a]

	PM10 Emissions (10^3t/yr)							
	Section							
Year	Pacific	Mountain	Northern Midwest	Southern Midwest	North Central	Northeast	Southeast	National Total
1978	221	298	348	255	985	620	1229	3956
1987	211	299	316	250	934	558	1249	3817
1989	211	303	312	253	932	549	1272	3833
1995	218	326	306	268	945	534	1383	3981

[a]Before application of control strategy.

[b]The states in each Section are given in Appendix B.

Table A.4 Nationwide Costs and Attainment Status

Scenario	Initial Nonattainment Areas	Cost of Strategy (10^6 $)[a,b] NPV	Cost of Strategy (10^6 $)[a,b] BTAC	Residual Nonattainment Areas	Estimated NPV Cost for Reduction of Residual Nonattainment (10^6 $)[b] Median	Estimated NPV Cost for Reduction of Residual Nonattainment (10^6 $)[b] Average
TSP(75,-)/87	288	2,009	425	139	346	3,012
TSP(-,150)/87	525	3,343	708	304	651	8,027
TSP(-,260)/87	155	757	160	73	19	687
TSP(75,150)/87	541	3,352	710	308	643	8,097
TSP(75,260)/87	300	2,046	433	150	356	3,052
TSP(-,150)/89	522	2,675	685	301	506	6,277
TSP(75,260)/89	299	1,624	416	147	0	2,296
PM10(55,-)/89	182	1,356	347	88	441	2,422
PM10(70,-)/89	83	705	181	41	129	681
PM10(90,-)/89	34	151	39	11	6	113
PM10(-,150)/89	312	1,757	450	158	129	3,094
PM10(-,200)/89	146	997	255	71	105	955
PM10(-,250)/89	80	488	125	32	7	373
PM10(-,300)/89	49	146	37	18	<1	111
PM10(55,150)/89	329	1,900	487	165	161	3,404
PM10(48,183)/89[c]	298	1,977	507	160	291	3,068
PM10(55,200)/89	205	1,426	365	102	408	2,379
PM10(55,250)/89	185	1,390	356	92	431	2,467
PM10(70,200)/89	155	1,030	264	78	148	975
PM10(70,250)/89	105	757	194	50	83	676
PM10(90,300)/89	55	195	50	19	6	135

[a]Strategy leaves some residual nonattainment.

[b]NPV: 1982 Net Present Value.
BTAC: Before Tax Annualized Cost.

[c]The $PM10_{}$ standards in this scenario approximate TSP standards of 75 $\mu g/m^3$, annual geometric mean, and 260 $\mu g/m^3$, second highest observed 24-hour value, in the sense that the PM10 values were derived from the TSP values for the same averaging time by applying the regression equations used elsewhere in this analysis to estimate missing air quality values and by applying the conversion ratio of 0.55 to convert TSP concentrations to PM10 concentrations.

Table A.5 Nationwide NPV Costs and Emission Reductions by Source Type

	1982 Net Present Value (10^6 $) and Emission Reductions Achieved (10^3 t/yr)[a,b]							
	Source Type							
	Stack		Nontraditional Fugitive		Paved Municipal Roads		National Total	
Scenario	NPV	ERA	NPV	ERA	NPV	ERA	NPV	ERA
TSP(75,-)/87	1751	515	222	157	36	7	2009	679
TSP(-/150)/87	2932	812	360	244	51	9	3343	1066
TSP(-,260)/87	629	235	109	94	18	3	757	332
TSP(75,150)/87	2939	816	362	245	51	9	3352	1070
TSP(75,260)/87	1780	524	229	159	37	7	2046	690
TSP(-,150)/89	2338	781	295	243	42	9	2675	1033
TSP(75,260)/89	1407	495	187	158	30	7	1624	660
PM10(55,-)/89	1210	240	125	58	21	3	1356	302
PM10(70,-)/89	633	108	61	32	11	2	705	142
PM10(90,-)/89	129	17	19	13	3	<1	151	31
PM10(-,150)/89	1545	316	185	80	28	4	1757	400
PM10(-,200)/89	890	138	92	48	15	2	997	189
PM10(-,250)/89	428	69	49	33	10	2	488	104
PM10(-,300)/89	119	23	24	17	4	<1	146	41
PM10(55,150)/89	1679	331	192	84	28	6	1900	419
PM10(48,183)/89[c]	1603	344	185	82	30	5	1977	431
PM10(55,200)/89	1271	247	133	61	22	4	1426	312
PM10(55,250)/89	1242	242	127	59	21	3	1390	304
PM10(70,200)/89	918	141	97	52	15	4	1030	195
PM10(70,250)/89	676	116	69	40	13	2	758	158
PM10(90,300)/89	162	27	29	19	4	1	195	46

[a] NPV: Net Present Value.
ERA: Emission Reduction Achieved.

[b] ERA given for pollutant corresponding to standard.

[c] The PM10 standards in this scenario approximate TSP standards of 75 $\mu g/m^3$, annual geometric mean, and 260 $\mu g/m^3$, second highest observed 24-hour value, in the sense that the PM10 values were derived from the TSP values for the same averaging time by applying the regression equations used elsewhere in this analysis to estimate missing air quality values and by applying the conversion ratio of 0.55 to convert TSP concentrations to PM10 concentrations.

Table A.6 NPV Costs and TSP Emission Reductions for Major Categories

SIC	Category	1982 Net Present Value ($10^6$$) and Emission Reduction Achieved (10^3t/yr)[a]													
		Scenario													
		TSP(75,-)/ 87		TSP(-,150)/ 87		TSP(-,260)/ 87		TSP(75,150)/ 87		TSP(75,260)/ 87		TSP(-,150)/ 89		TSP(75,260)/ 89	
		NPV	ERA	NPV	ERA	NPV	ERA	NPV	ERA	NPV	ERA	NPV	ERA	NPV	ERA
-	Municipal Paved Roads	36	7	51	9	18	3	51	9	37	7	42	9	30	7
4911	Utility Power Plants	698	245	1243	428	277	117	1245	429	706	246	997	422	561	235
3312	Iron and Steel	366	136	525	197	101	64	523	197	366	137	423	191	291	127
2951	Paving Mixtures	54	16	93	21	29	8	96	21	57	16	75	21	46	15
3241	Hydraulic Cement	59	52	84	65	6	12	84	65	59	53	66	58	48	51
2621	Paper Mills, Except Building Paper	29	5	72	10	15	3	72	10	29	5	57	9	23	5
1422	Crushed and Broken Limestone	28	11	69	16	3	1	68	16	28	11	55	15	23	11
3295	Ground or Treated Minerals	48	34	62	42	35	29	61	42	49	34	49	41	39	33
4961	Steam Supply	51	5	61	6	14	2	60	6	51	5	49	6	41	5
5153	Wholesale Grain	29	9	54	20	14	4	56	20	32	11	42	19	25	10
3321	Gray Iron Foundries	43	3	53	3	22	1	55	3	43	3	42	3	34	2
3331	Primary Copper Smelters	5	1	14	4	3	1	14	4	5	1	11	4	4	2
All SICs National Total		2009	679	3343	1066	757	332	3352	1070	2046	690	2675	1033	1624	660

[a]NPV: Net Present Value.
ERA: TSP Emission Reduction Achieved.

Table A.7 NPV Costs and PM10 Emission Reductions for Major Categories

SIC	Category	1982 Net Present Value ($10^6$$) and Emission Reduction Achieved (10^3t/yr)[a]																			
		Scenario																			
		PM10(55,-)/89		PM10(70,-)/89		PM10(90,-)/89		PM10(-,150)/89		PM10(-,200)/89		PM10(-,250)/89		PM10(48,183)/89[b]		PM10(55,200)/89		PM10(55,250)/89		PM10(70,250)/89	
		NPV	ERA	NPV	ERA	NPV	ERA	NPV	ERA	NPV	ERA	NPV	ERA	NPV	ERA	NPV	ERA	NPV	ERA	NPV	ERA
-	Municipal Paved Roads	21	3	11	2	3	<1	28	4	15	2	10	2	30	5	22	2	21	3	13	2
4911	Utility Power Plants	464	123	203	50	83	13	554	150	326	54	138	27	610	161	487	125	484	123	228	54
3312	Iron and Steel	263	49	175	26	6	2	317	61	196	32	104	14	398	70	264	50	263	49	175	26
2951	Paving Mixtures and Blocks	32	5	16	2	5	1	47	6	23	3	12	2	45	6	33	5	32	5	18	2
3241	Hydraulic Cement	35	15	29	10	2	2	52	20	35	12	28	8	64	33	40	17	35	15	30	10
2621	Paper Mills, Except Building Paper	18	2	11	1	9	1	22	2	14	1	9	1	24	3	19	2	18	2	11	1
1422	Crushed and Broken Limestone	6	2	2	<1	<1	<1	15	5	3	1	2	<1	15	5	6	2	6	2	2	1
3295	Ground or Treated Minerals	35	23	23	20	3	<1	45	24	32	21	22	20	43	23	37	23	35	23	24	21
4961	Steam Supply	43	3	39	2	1	<1	43	3	19	2	17	1	50	4	43	3	43	3	39	2
5153	Wholesale Grain	11	5	6	2	2	1	18	8	11	3	8	3	25	9	14	6	12	5	8	3
3321	Gray Iron Foundries	19	1	11	<1	2	<1	38	2	22	1	3	<1	38	2	29	1	19	1	11	<1
3331	Primary Copper Smelters	5	1	2	<1	1	<1	12	2	4	<1	4	<1	12	2	5	1	5	1	4	<1
All SICs	National Total	1356	302	705	142	151	31	1757	400	997	189	488	104	1977	431	1426	312	1390	304	757	158

[a] NPV: Net Present Value.
ERA: PM10 Emission Reduction Achieved.

[b] The PM10 standards in this scenario approximate TSP standards of 75 $\mu g/m^3$, annual geometric mean, and 260 $\mu g/m^3$, second highest observed 24-hour value, in the sense that the PM10 values were derived from the TSP values for the same averaging time by applying the regression equations used elsewhere in this analysis to estimate missing air quality values and by applying the conversion ratio of 0.55 to convert TSP concentrations to PM10 concentrations.

Table A.8 Regional NPV Costs and Attainment Status[a]

	1982 Net Present Value (10^6 $) and Initial/Residual Nonattainment Status[b,c]																			
	Region																			
	I		II		III		IV		V		VI		VII		VIII		IX		X	
Scenario	NPV	NAA	NPV	NAA	NPV	NAA	NPV	NAA	NPV	NAA	NPV	NAA	NPV	NAA	NPV	NAA	NPV	NAA	NPV	NAA
TSP(75,150)/87	89	20/11	101	13/9	384	45/21	477	88/42	1406	134/71	152	50/31	257	67/18	172	33/22	210	47/42	104	44/41
TSP(75,260)/87	23	4/2	41	5/1	294	24/9	265	39/16	827	70/28	94	28/13	102	38/7	133	19/14	204	41/36	63	32/24
TSP(-150,)/89	66	19/11	80	13/9	317	45/20	382	86/42	123	131/69	119	45/30	200	62/17	135	32/21	169	45/41	84	44/41
TSP(75,260)/89	17	4/2	33	5/1	229	24/7	213	39/15	660	70/28	75	28/13	76	38/7	106	19/14	164	40/36	51	32/24
PM10(48,183)/89[d]	18	6/1	53	6/1	274	24/6	280	33/19	758	70/29	122	41/26	88	25/3	135	19/15	194	39/35	57	35/25
PM10(55,200)/89	1	3/0	6	3/0	118	14/2	258	16/11	609	44/16	88	31/17	33	16/2	82	15/6	188	37/32	42	26/16
PM10(55,250)/89	1	2/0	3	2/0	117	11/1	256	15/10	595	40/15	87	29/15	24	15/2	82	13/6	186	37/31	37	21/12
PM10(70,250)/89	0	0/0	<1	1/0	13	6/1	77	7/2	355	23/6	75	15/9	15	6/2	59	8/2	136	25/19	27	14/9

[a]The states in each Region are given in Appendix B.

[b]NPV: Net Present Value.
NAA: Number of Nonattainment Areas.

[c]NAA entries give (Initial NAA)/(Residual NAA).

[d]The PM10 standards in this scenario approximate TSP standards of 75 $\mu g/m^3$, annual geometric mean, and 260 $\mu g/m^3$, second highest observed 24-hour value, in the sense that the PM10 values were derived from the TSP values for the same averaging time by applying the regression equations used elsewhere in this analysis to estimate missing air quality values and by applying the conversion ratio of 0.55 to convert TSP concentrations to PM10 concentrations.

Table A.9 Sectional NPV Costs and Attainment Status[a]

	1982 Net Present Value ($10^6$$) and Initial/Residual Nonattainment Status[b,c]													
	Section													
	Pacific		Mountain		Northern Midwest		Southern Midwest		North Central		Northeast		Southeast	
Scenario	NPV	NAA	NPV	NAA	NPV	NAA	NPV	NAA	NPV	NAA	NPV	NAA	NPV	NAA
TSP(75,150)/87	150	52/46	360	82/68	302	83/23	126	37/22	1363	121/66	541	56/30	510	110/53
TSP(75,260)/87	109	39/29	308	60/51	104	47/8	78	20/7	826	62/27	345	21/7	277	51/21
TSP(-,150)/89	121	50/46	286	81/66	234	77/21	98	32/21	1091	119/65	437	55/29	409	108/53
TSP(75,260)/89	88	38/29	246	60/51	78	47/8	62	20/7	658	62/27	270	21/7	221	51/18
PM10(48,183)/89[d]	122	39/30	279	61/52	89	33/4	105	33/19	757	63/28	323	25/6	302	44/21
PM10(55,200)/89	109	29/22	214	57/37	33	18/3	77	23/12	608	42/15	124	13/0	260	23/13
PM10(55,250)/89	104	24/18	213	55/36	25	16/3	76	21/10	595	39/14	120	10/0	257	20/11
PM10(70,250)/89	88	17/12	141	35/21	15	7/2	67	10/6	355	22/6	13	6/0	77	8/3

[a]The states in each Section are given in Appendix B.

[b]NPV: Net Present Value.
NAA: Number of Nonattainment Areas.

[c]NAA Entries give (Initial NAA)/(Residual NAA).

[d]The PM10 standards in this scenario approximate TSP standards of 75 $\mu g/m^3$, annual geometric mean, and 260 $\mu g/m^3$, second highest observed 24-hour value, in the sense that the PM10 values were derived from the TSP values for the same averaging time by applying the regression equations used elsewhere in this analysis to estimate missing air quality values and by applying the conversion ratio of 0.55 to convert TSP concentrations to PM10 concentrations.

Table A.10 Estimated Nationwide Costs Including Reduction of Residual Nonattainment

Scenario	Cost Including Reduction of Residual Nonattainment[a]		
	CAP(10^6\$)	BTAC(10^6\$/yr)	NPV(10^6\$)
TSP(75,-)/87	6,340	1,060	5,020
TSP(-,150)/87	14,550	2,410	11,370
TSP(-,260)/87	1,770	310	1,440
TSP(75,150)/87	14,650	2,420	11,450
TSP(75,260)/87	6,420	1,080	5,100
TSP(-,150)/89	13,820	2,290	8,950
TSP(-,260)/89	5,950	1,000	3,920
PM10(55,-)/89	5,850	970	3,780
PM10(70,-)/89	2,110	360	1,390
PM10(90,-)/89	420	70	260
PM10(-,150)/89	7,460	1,240	4,850
PM10(-,200)/89	3,080	500	1,950
PM10(-,250)/89	1,280	220	860
PM10(-,300)/89	400	70	260
PM10(55,150)/89	8,200	1,360	5,300
PM10(48,183)/89[b]	8,480	1,390	5,440
PM10(55,200)/89	5,910	970	3,810
PM10(55,250)/89	5,990	990	3,860
PM10(70,200)/89	3,140	510	2,000
PM10(70,250)/89	2,190	370	1,430
PM10(90,300)/89	510	80	330

[a]CAP: Capital Cost.
BTAC: Before Tax Annualized Cost.
NPV: 1982 Net Present Value

[b]The PM10 standards in this scenario approximate TSP standards of 75 $\mu g/m^3$, annual geometric mean, and 260 $\mu g/m^3$, second highest observed 24-hour value, in the sense that the PM10 values were derived from the TSP values for the same averaging time by applying the regression equations used elsewhere in this analysis to estimate missing air quality values and by applying the conversion ratio of 0.55 to convert TSP concentrations to PM10 concentrations.

Appendix B Regions and Sections

Table B.1 lists the states by EPA Region as used in the preparation of Regional reports. These are the standard EPA administrative Regions. Table B.2 lists the states by Section as defined for this work.

Table B.1 States by Region

Region	States	Region	States
I	Connecticut	VI	Arkansas
	Maine		Louisiana
	Massachusetts		New Mexico
	New Hampshire		Oklahoma
	Rhode Island		Texas
	Vermont		
II	New Jersey	VII	Iowa
	New York		Kansas
	Puerto Rico		Missiouri
	Virgin Islandsa		Nebraska
III	Delaware	VIII	Colorado
	Dist. of Columbia		Montana
	Maryland		North Dakota
	Pennsylvania		South Dakota
	Virginia		Utah
	West Virginia		Wyoming
IV	Alabama	IX	American Samoa[a]
	Florida		Arizona
	Georgia		California
	Kentucky		Guam[a]
	Missippi		Hawaii
	North Carolina		Nevada
	South Carolina		
	Tennessee		
V	Illinois	X	Alaska
	Indiana		Idaho
	Michigan		Oregon
	Minnesota		Washington
	Ohio		
	Wisconsin		

[a]Not included in this analysis.

Table B.2 States by Section

Section	States	Section	States
1. Pacific	Alaska	5. North Central	Illinois
	California		Indiana
	Hawaii		Michigan
	Oregon		Ohio
	Washington		Wisconsin
		6. Northeast	Connecticut
2. Mountain	Arizona		Maine
	Colorado		Massachusetts
	Idaho		New Hampshire
	Montana		New Jersey
	Nevada		New York
	New Mexico		Pennsylvania
	Utah		Rhode Island
	Wyoming		Vermont
		7. Southeast	Alabama
3. Midwest	Iowa		Delaware
	Kansas		Dist. of Columbia
	Minnesota		Florida
	Missouri		Georgia
	Nebraska		Kentucky
	North Dakota		Maryland
	South Dakota		Mississippi
			North Carolina
			Puerto Rico
4. South Midwest	Arkansas		South Carolina
	Louisiana		Tennessee
	Oklahoma		Virginia
	Texas		West Virginia
5. North Central	Illinois		
	Indiana		
	Michigan		
	Ohio		
	Wisconsin		

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